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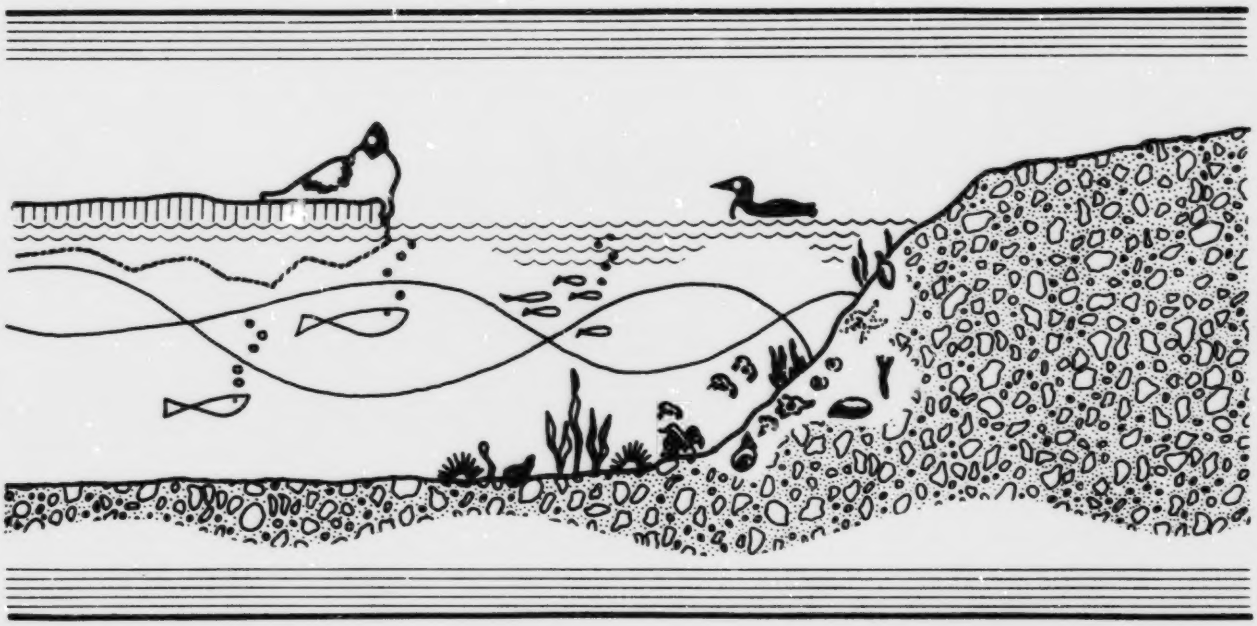
SPECIAL STUDIES



Baffin Island Oil Spill Project

WORKING REPORT SERIES

1982 STUDY RESULTS

FOREWORD

SPECIAL STUDIES 1982

This publication presents the results of selected studies which were associated with the Baffin Island Oil Spill (BIOS) Project or which were carried out at the BIOS Project site of Cape Hatt, Baffin Island. These studies were ancillary to the original design and/or core programs of the Project and, due to financial limitations, the BIOS Project did not directly fund them. Nevertheless, the study results are of relevance to the BIOS Project and are provided in order to both enhance the understanding of BIOS Project findings and to transfer the information to people working in related research. This publication has not undergone rigorous technical review by the BIOS management or technical committees and does not necessarily reflect the view of policies of these groups.

Three reports are contained herein:
The first report presents the second year of a two-year study on the effects of oil on under-ice biota. Portions of the under-ice experiment are related to the interpretation of effects from the original BIOS oil releases.

The second report contains information relevant to the BIOS dispersed oil discharge system design and the understanding of dispersed oil particle behaviour.

The third report describes a spin-off pilot study initiated after observing certain effects caused by the BIOS Project dispersed oil release. This study was expanded and continued with BIOS Project funding in 1983.

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2. Mackay, D., Hossain, K., Chau, E., Poblete, B. and Nilsson, U., 1983, Behaviour of Subsurface Discharges of Oil, Gas and Dispersants. Special Studies - 1982 Study Results. (BIOS) Baffin Island Oil Spill Working Report 82-7.

3. Engelhardt, R., Mageau, C. and Trucco, R., 1983, Behaviour Responses of Benthic Invertebrates Exposed to Dispersed Crude Oil. Proceedings of the Sixth Arctic Marine Oilspill Program Technical Seminar. pg. 32-51.

BAFFIN ISLAND OIL SPILL PROGRAM

SPECIAL STUDIES

1982 STUDY RESULTS

Part I: *In Situ* Studies of Effects of Oil and Chemically Treated Oil on Primary Productivity of Ice Algae and on Under-ice Meiofaunal and Macrofaunal Communities

Part II: Behaviour of Subsurface Discharges of Oil, Gas and Dispersants

Part III: Behavioural Responses of Benthic Invertebrates Exposed to Dispersed Crude Oil

December, 1983

In Situ STUDIES OF EFFECTS OF OIL AND CHEMICALLY TREATED OIL ON PRIMARY PRODUCTIVITY OF ICE ALGAE AND ON UNDER-ICE MEIOFAUNAL AND MACROFAUNAL COMMUNITIES

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November 1983

EXECUTIVE SUMMARY

Effects of in situ applications of oil and chemically treated oil on the under-ice algae, meiofauna and amphipods were studied at Cape Hatt, northern Baffin Island. Immediate effects of oil on ice algae and meiofauna were studied by adding oil, solidified oil and oil treated with three different dispersants (Corexit 9527, BP 1100WD, BP CTD) into large enclosures on the under-ice surface. The abundance and productivity of ice algae and the abundance of meiofauna were studied. In addition, distribution and life history data were collected for amphipods occupying under-ice, intertidal and shallow sublittoral habitats. The latter component of the study utilized the large-scale experimental spills carried out at the BIOS (Baffin Island Oil Spill) site in August 1981; we obtained pre-spill (May and August 1981) and post-spill (September 1981 and August and September 1982) data.

Methods.--Field studies were carried out during 16-31 May, 10-19 August and 7-8 September 1981, and during 8 May-2 June, 20-25 August and 6-11 September 1982 from the BIOS (Baffin Island Oil Spill) project base camp located at Cape Hatt, Baffin Island. The study area consisted of five shallow embayments in Ragged Channel, some 5-8 km SSE of Cape Hatt. All under-ice and sublittoral sampling and experimental work was carried out by SCUBA divers working through holes in the ice (May) or from small inflatable boats (August and September). Studies on amphipod distribution and population structure were conducted in four small bays at a depth of 3-5 m, or on the ice undersurface at the same locations; intertidal sampling was carried out 150 m of beach within each of the BIOS study bays. Experimental

studies on ice algae and meiofaunal communities were conducted on the under-ice surface in another bay over a water depth of 10 m.

Quantitative samples of amphipods were collected in the under-ice habitat at two times in May 1981 and 1982; in the shallow (3-5 m) sublittoral habitat in May, August and September 1981 and 1982; and in the intertidal habitat in August and September 1981 and 1982. Amphipods were identified, counted, weighed and measured. Spatial, seasonal and habitat variability in species composition, distribution and population structures, together with the effects of experimental oil releases in August 1981, were examined using ANOVA techniques.

The effects of treated and untreated oil on under-ice communities were studied during 14 May-2 June 1982. Productivity of under-ice algae was determined by a modification of the standard ^{14}C light and dark bottle technique (Strickland and Parsons 1972); ice and water samples were incubated in situ for 2 h periods. We attempted to trace carbon pathways in arctic under-ice comunities by utilizing labelling and differential filtration to separate dissolved organic carbon and the particulate organic carbon contained in bacteria, algae and their meiofaunal consumers. We also compared these results with production estimates based on repeated measures of photosynthetic pigments, particulate organic carbon, and numbers and species or group composition of microalgae and meiofauna. Ratios between the various measures of standing stock were employed to obtain estimates of the physiological condition of the microalgae. The effects of oil, dispersed oil and solidified oil on production and productivity were determined relative to temporal and spatial controls.

Macrofauna.--The under-ice macrofauna in the three study bays included arctic cod (*Boreogadus saida*) and mysids (*Mysis* spp.), but otherwise consisted entirely of gammarid amphipods. Cod were observed only in the large tide cracks just inshore of the entry holes in each of the bays. Mysids were present throughout the water column in each bay, and were generally concentrated in the first metre of water just below the ice; mysid densities were extremely high and variable both within and among bays.

Ten and thirteen species of gammarid amphipods were collected on the under-ice surface at Cape Hatt in 1981 and 1982, respectively. Two species, *Ischyrocerus* sp. and *Weyprechtia pinguis*, were dominant in terms of numbers in both years, and *Onisimus* juveniles were abundant only in 1982. *Weyprechtia pinguis* and *Gammarus setosus* were dominant in terms of biomass in both years. Four and eighteen amphipod species were collected in the intertidal habitat in 1981 and 1982, respectively. *Gammarus setosus* was dominant in terms of both numbers and biomass in both years; *Onisimus litoralis* and *Onisimus glacialis* were abundant only in 1982. In the shallow (3-4 m) sublittoral habitat, 38 and 33 species were collected in 1981 and 1982, respectively. In both years, *Orchomene minuta* and *Guernea* sp. were dominant in terms of numbers, and *Orchomene minuta*, *Anonyx nugax* and *Anonyx sarsi* were dominant in terms of biomass.

Aside from *Apherusa glacialis*, all of the other species that were common on the under-ice surface were clearly of benthic origin. *Apherusa glacialis* was present only in May (under-ice and sublittoral habitats), and is commonly associated with pan ice in the open water season. *Gammarus setosus*, *Onisimus litoralis* and *Onisimus glacialis* almost exclusively inhabited intertidal areas during the ice-free season. Weyprechtia pinguis and Ischyrocerus sp., on the other hand, were more common in sublittoral than in intertidal habitats during summer. Species that were very rare on the under-ice surface together comprised a large percentage of the amphipods collected in the sublittoral habitat. Their occasional presence on the under-ice surface was likely due to chance.

Amphipod distribution on the under-ice surface was patchy, and was apparently related to the distribution of under-ice algae. In general, there were pronounced among bay differences in amphipod abundances. Analyses of variance and inspection of the data showed that each of the dominant species was more abundant in some bays than others. Both year-to-year and seasonal variability were evident in the densities of under-ice amphipods. The predominant seasonal trend was an increase in density from early to late May, and the predominant annual trend was a decrease in numbers or biomass from 1981 to 1982. Onisimus juveniles were the one exception: numbers increased markedly in all bays from 1981 to 1982.

Differences among bays in the densities and biomass of intertidal amphipods were considerable in both 1981 and 1982. During 1981, differences between August and September in abundance and biomass of the dominant intertidal amphipods were not consistent among bays. In 1982, differences between August and September were significant only for Onisimus litoralis and Onisimus glacialis: the former increased in abundance between August and September, whereas densities of Onisimus glacialis were generally lower in September. Year-to-year differences in the abundance and biomass of intertidal amphipods were considerable.

These differences may represent a real change in amphipod distributions from one year to the other. Higher 1982 densities of *Onisimus glacialis*, for example, are likely related to the observed increases in densities of *Onisimus* juveniles under the ice in May. In turn, this indicates that 1981 was a year of successful breeding, at least in some locations. Year-to-year differences may also be related to year-to-year differences in tide levels in combination with substrate differences within bays, or to some other type of sampling bias.

Significant interaction terms in analyses of variance have indicated oil effects on dominant amphipods in both under-ice and intertidal habitats. There was an unequivocal effect of the surface oil release in Bay 11 on *Gammarus setosus*. Direct oiling of intertidal populations in Bay 11 caused immediate mortality. Densities in this bay were significantly reduced three weeks after the oil release, particularly in the 0+ year class. This cohort was almost absent from the under-ice surface in the following spring but was well represented in the intertidal habitat one year following the oil release. These individuals must have been recruited from adjacent areas. Larvigerous females were present on the under-ice surface in Bay 11 in May of both the pre- and the post-spill years, but the release of juveniles was delayed in 1982. This delay apparently resulted in reduced size of the 1982 0+ year class in the intertidal habitat in August and September.

The dispersed oil release, on the other hand, seems to have affected older *Gammarus setosus* (1 and 2+ year classes). Densities of these individuals were markedly reduced approximately one week following the release, but it is uncertain whether mortality or emigration was the cause of this decrease. Densities on the under-ice surface were low in both the pre- and the post-spill years. No effects were apparent in abundance and population structure data collected in the intertidal habitat one year following the release.

Increases in density and biomass of juvenile Onisimus from 1981 to 1982 were much more pronounced in Bay 10 (some dispersed oil contamination) than in Bays 9 (dispersed oil release) or 11 (surface oil release). These differences, together with the observed high densities of these juveniles in Bay 7 (reference bay) during May 1982, suggest that a natural population increase from 1981 to 1982 may have been partly inhibited in bays that received high levels of dispersed oil (Bay 9) or surface oil (Bay 11).

Ischyrocerus sp. was sparsely distributed in the sublittoral habitat of Bay 9 at the time of the dispersed oil release. Population structures of Ischyrocerus sp. on the under-ice surface indicated that under-ice populations of this species at Cape Hatt are of benthic rather than pelagic origin, and furthermore, that these populations are relatively immobile on a large (bay) scale. Biomass of Ischyrocerus sp. on the under-ice surface decreased significantly from late May 1981 to late May 1982 in Bay 9 but not in Bays 10 or 11. This suggests that biomass was reduced by the dispersed oil released in Bay 9 between the two sampling dates. Differences in the results for density and biomass suggest that there were size-specific effects. Additional spring sampling in subsequent years would be required to determine if populations of this species in the dispersed oil bay will recover.

Microalgae.--Phytoplankton in the water immediately below the ice at Cape Hatt during May 1982 occurred at low concentrations ($<10^4$ cells/L), and consisted primarily of pennate diatoms (48% of cell numbers) and microflagellates (45%). Biomass (chlorophyll *a* concentration) and productivity were also very low in sub-ice water during May 1981 and 1982-- 2 to 3 orders of magnitude below those in the bottom layer of ice. In both years, chlorophyll *a* concentrations were <2 mg/m^3, and net productivity rates (calculated by subtracting dark values from values measured in light chambers) were slightly negative.

The ice algal community in the bottom layer of ice during May 1982 was dominated by pennate diatoms (89% of algal cells in 83 control samples). Sixty-one of the total of 76 species or varieties of microalgae identified were pennate diatoms. *Nitzschia grunowii* and *N. frigida* were the most common species collected, comprising 54.8% and 15.2%, respectively, of total cell numbers in control samples. Total densities ranged from 1.7 to 384.7 x 10^7 cells/m^2, and mean densities increased progressively throughout the study period. Cell densities in most locations at Cape Hatt were typical of those reported for other arctic locations.

Differential filtration procedures were used to attempt to separate algae (>3 µm) from bacteria (<3 µm, >0.45 µm). Results of comparisons between filter types, however, indicated the possibility that the high concentrations of algae present in samples resulted in clogging of filters, rupture of algal cells and loss of cell contents through the filters. Thus, reported values of particulate organic carbon productivity (i.e. ^{14}C retained on filters) may underestimate actual carbon fixation by ice microalgae. Different techniques were used to estimate dissolved organic carbon (DOC) productivity (smaller sample volumes, lower filtration pressure), and the reported values for DOC are considered to be more realistic estimates. For comparative purposes, all data reported herein are based on the filter type in most common use (0.45 µm pore size).

Chlorophyll a concentrations in control ice samples varied from 0.6 to 23.2 mg/m^2; mean chlorophyll concentration increased from 9.1 mg/m^2 on 18-19 May to 15.7 mg/m^2 on 1-2 June 1982. Carbon to chlorophyll ratios for the ice algal community increased from 16 to 30 over the study period. A similar increase in chlorophyll concentration (6.6 to 10.9 mg/m^2) occurred at Cape Hatt during 16-30 May 1981, and these values are typical of ice algal biomass reported in a number of other arctic locations. Considerably higher concentrations of chlorophyll under the ice have been reported (e.g., in Pond Inlet during 1979; Cross 1982a), and differences are likely a result of differences in snow cover.

The amount of light reaching the under-ice surface at Cape Hatt in 1982 varied over an order magnitude because of variability in snow cover and sky condition. Particulate carbon productivity of ice algae increased with increasing light, from near zero at the lowest light levels to a maximum of 2.95 mgC/m^2.h. Productivity and productivity per unit chlorophyll increased over the study period. Our data on particulate carbon productivity from 1982 are similar to those from Cape Hatt in May 1981 (Cross 1982b) and from Barrow, Alaska in May-June 1972 (Clasby et al. 1973).

Productivity rates of dissolved organic carbon (DOC) have not previously been measured for under-ice algae. At Cape Hatt in 1982 DOC productivity was considerably higher than particulate carbon productivity: from 0.1 to 9.3 $mgC/m^2.h$ (overall mean of 3.3 $mgC/m^2.h$). Regardless of the source of the observed radioactive DOC, this material was originally fixed by ice algae, and must be included in estimates of total productivity. On average, DOC accounted for 70% of total (particulate + dissolved) carbon production. If such high DOC productivity is characteristic of the ice algae community, previous reports on particulate carbon fixation may have underestimated ice algal productivity to a significant extent.

Standing stocks and productivity of under-ice algae were measured before and after treatment with crude oil (Venezuela Lagomedio), solidified oil (BP treatment), oil mixed with each of three dispersants (Corexit 9527, BP 1100 WD and BP CTD), and no oil (control). Dispersed oil, in concentrations between 5.8 and 36.5 ppm, was contained within enclosures beneath the ice for approximately five hours. Oil and solidified oil remained in the enclosures on the under-ice surface during post-treatment sampling periods, and sampling was carried out within the enclosures but not directly in the oiled areas. Oil concentrations in the water within enclosures containing oil and solidified oil, measured 5 h after treatment, were similar to control values.

Analysis of variance was applied to data on standing stocks and productivity, and to ratios calculated to standardize for light effects: standing stocks/percent transmission, and productivity/in situ light during incubations. Productivity per unit of chlorophyll and productivity per unit chlorophyll per unit light were also subjected to analysis of variance. Most interactions between period and treatment factors were significant (13 of 16 cases). In these cases, the significant interaction terms meant that period-to-period variation was not consistent among treatments, indicating the possibility of an oil effect. However, other factors besides the treatment could also lead to significant interaction terms. It was, therefore, necessary to examine the nature of the period-to-period variability among treatments to determine whether it was consistent with expected oil effects.

Inspection of the data showed little evidence for any of the expected oil effects. There were no marked deleterious effects of any oil treatment on any of the variables. Decreases in some or all variables from the immediate pre-spill to immediate post-spill periods were evident in some enclosures,but these generally corresponded with decreases in light, and were also evident in the control. There were no marked immediate effects of dispersed oil treatments, nor was there any evidence of recovery in later post-spill periods. Differences among dispersants or between locations were not consistent with measured oil concentrations.

Inspection of the data for oil and solidified oil treatments indicated the possibility of a stimulation effect of these treatments on the biomass and productivity of under-ice algae. Progressive (period-to-period) increases in biological variables were not common in any treatment except the solidified oil and, to a lesser extent, untreated oil treatments. This progressive increase was not clearly related to increases in light, particularly in the case of the solidified oil treatment. In some cases, however, increases in biological variables at these locations were also apparent between the two pre-spill periods. Increases in biomass and productivity are typical of under-ice algae during the spring before the peak of the bloom and were also evident in control samples at Cape Hatt during May 1981 and 1982. Differences among enclosures (treatments) in the nature of the increases may also be related to snow conditions, and in particular, changes in snow depth that occurred immediately before the study period.

In the present study, we attempted to create realistic scenarios for the impingement of oil onto the under-ice surface: low concentrations of dispersed oil contacting the ice for a short period of time, and untreated oil and solidified oil remaining in place on the under-ice surface. Analyses and inspection of the data showed considerable spatial and temporal variability in productivity and standing stocks of under-ice algae, but there was little evidence for any of the expected oil effects.

Meiofauna.--The under-ice meiofauna (invertebrates in the size range 40 µm to 1 mm) collected at Cape Hatt during 18 May-2 June 1982 included copepods, nematodes, polychaete larvae, rotifers and gastropod veligers. Copepods, the numerically dominant taxon, comprised 89.3% of total numbers collected during the study. Nematodes and polychaetes made up 6.3% and 3.5% of total numbers, respectively. Rotifers and gastropod veligers were also present in very small numbers. Cyclopoid and harpacticoid copepods comprised 82.3% and 17.2%, respectively, of the ice copepod fauna. Calanoid copepods were only represented by nauplii and accounted for the remainder of total numbers. A total of six species of cyclopoid and harpacticoid copepods were collected in systematic samples from the under-ice surface.

Total meiofaunal densities at the productivity site in Bay 13 (control samples only) averaged approximately 54,000 individuals/m^2; copepods alone contributed about 50,000 ind./m^2. Under-ice copepod densities were higher, and nematode densities generally lower, than those previously reported in arctic and sub-arctic waters. Meiofauna were relatively evenly distributed on a small scale (i.e.. within the 1.2 m^2 enclosures), whereas variation on a larger scale (among enclosures in Bay 13 and among bays) was considerable, and was evident for all meiofaunal groups.

There are several possible sources of this large scale variability, including snow depth, light intensity and concentrations of microalgae. Light level was positively correlated with densities of nematodes, copepods and, to a lesser extent, polychaetes. Similar correlations were evident between chlorophyll a concentrations and the densities of each of these groups.

Nematode densities in unoiled control samples increased significantly over the study period, whereas copepod and polychaete abundances in control samples from Bay 13 were relatively constant over the study period. However, this was not true for all particular types of copepods. Densities of cyclopoid copepodites decreased from 18 May-2 June; at the same time, densities of cyclopoid adults increased. In contrast, harpacticoid copepods showed no obvious temporal variation related to stages of development.

Analysis of variance showed significant treatment x period interactions (oil effects) for two of the meiofaunal groups, copepods and polychaetes. Copepod and polychaete densities decreased dramatically between pre-spill and post-spill periods in each of the three dispersed oil treatments in each location; densities in the other three treatments (control, solidified oil and oil) remained relatively constant. Nematodes were unaffected by any of the oil treatments; densities increased throughout the study period in each treatment and in each location. The observed reductions in copepod and polychaete densities were similar for the three types of dispersants and the two locations, irrespective of the differences in oil concentrations measured within the enclosures (6-37 ppm).

Densities of polychaetes and copepods in dispersed oil treatments increased slightly during the post-spill period. This increase was more apparent for copepods than for polychaetes, probably indicating a faster recovery rate. It is not known whether the copepods or polychaetes were killed outright or merely displaced from the ice undersurface.

Copepod densities decreased in response to dispersed oil, whereas nematode densities did not. The differences in our results for copepods and nematodes are consistent with a current theory that the ratio of nematodes to copepods is a potentially useful tool in monitoring organic pollution, including oil pollution (Raffaelli and Mason 1981; Warwick 1981; cf. Coull et al. 1981). In the four BIOS study bays at Cape Hatt, nematode to copepod ratios were low in May 1982. If this type of ratio does prove to be a useful indicator of pollution in under-ice communities, the conclusion would follow that the Cape Hatt/Ragged Channel area is a non- polluted environment in spite of the experimental releases of oil carried out in 1981.

In view of the contradictory and limited data available on the effects of oil on meiofauna, however, we must be cautious in using such a simple ratio as a pollution indicator. In addition, too few data are available concerning the composition of the under-ice meiofaunal community under pristine conditions, and on natural factors affecting the distributions of copepods and nematodes.

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INTRODUCTION

In spring, a dense growth or bloom of microalgae occurs on and in the soft bottom layer of arctic sea ice. This algal layer begins to develop in April and the bloom peaks in May (Horner 1976, 1977). Productivity of ice algae during the relatively short bloom in April and May can be quite high. The bloom has been estimated to provide between 6 and 33% of the total annual primary production in various arctic locations (Alexander 1974; Horner et al. 1974; Welch and Kalff 1975). In addition, this bloom is important because its production occurs before there is significant production by planktonic and benthic algae during the open water season (Apollonio 1965). Thus, ice algal production is available to herbivores earlier in the season than is planktonic production (Dunbar 1968). This availability is further enhanced by the concentration of ice algae in two dimensions on the bottom of the ice and, near the end of the bloom, by their occurrence as macroscopic 'detrital' masses on the under-ice surface and in the water column (Cross 1982a).

In addition to the photosynthetic activity of its microalgae, the under-ice community also shows considerable heterotrophic activity. The heterotrophic component includes a number of microscopic organisms that can occur in abundance, including bacteria, fungi, colourless flagellates and ciliated protozoans (Horner 1976, 1977). The existence of an active microbial population is suggested both by the abundance of bacteria (Horner 1976) and by the uptake of labelled organic substrates (Horner and Alexander 1972). Considerable grazing activity among micro-organisms (e.g. flagellates ingest diatoms; ciliated protozoans graze on diatoms, bacteria and other organic material--Horner and Alexander 1972) further indicates the existence of an efficient system of in situ nutrient regeneration and inorganic carbon cycling. Inorganic nutrient concentrations in the bottom layer of ice are usually about an order of magnitude higher than in the water below (Horner 1976, 1977), in spite of the high algal concentrations occurring there. In addition to in situ nutrient regeneration, nutrient sources include drainage from the ice above and exchange with the water below (Meguro et al. 1967; Alexander et al. 1974).

The under-ice community also includes a wide variety of metazoans that graze on ice algae (Horner and Alexander 1972; Bradstreet and Cross 1982; Grainger and Hsiao 1982) and, presumably, on bacteria as well. The smallest of these metazoans--copepods, nematodes, polychaetes and turbellarians--are termed meiofauna. Interest in this community has increased in recent years. The existing literature is largely limited to sublittoral and intertidal habitats, but quantitative data on under-ice meiofaunal communities in arctic waters are becoming increasingly available (Thomson et al. 1978; Carey and Montagna 1982; Cross 1982a; Grainger and Hsiao 1982; Kern and Carey 1983). The impact of these grazers on ice-algal production, and their contribution to higher trophic levels (e.g. arctic cod--Bradstreet and Cross 1982), are not well understood. In consideration of their high abundances (on the order of 10^5 individuals/m^2), however, they may be extremely important in both respects.

The largest and most conspicuous invertebrates inhabiting the under-ice surface are gammarid amphiphods. Dominant species on the undersurface of the ice have included, at various places and times, Onisimus litoralis or

Onisimus glacialis (Green and Steele 1975; Buchanan et al. 1977; Thomson et al. 1978; Cross 1980, 1982a; Grainger and Hsiao 1982), Gammarus setosus (Thomson et al. 1978), Ischyrocerus anguipes (Cross 1980, 1982a,b), Apherusa glacialis (Golikov and Scarlato 1973; Cross 1980, 1982a) and Weyprechtia pinguis (Cross 1982b). Most of these species are herbivores that consume ice algae (e.g., Horner and Alexander 1972; Buchanan et al. 1977; Bradstreet and Cross 1980, 1982); Onisimus litoralis is also known as a scavenger of dead animal material (e.g., MacGinitie 1955). The habitats of these species in the absence of landfast ice include the undersurface of pan ice, the water column, and shallow sublittoral and intertidal areas. In the absence of ice, Apherusa glacialis and Onisimus glacialis are generally considered to be pelagic species (Dunbar 1954; Barnard 1959). However, Apherusa glacialis often associates with pan ice in late summer (e.g., Stephensen 1942; MacGinitie 1955; Divoky 1978; Thomson et al. 1978) and Onisimus glacialis is also an epibenthic species in some locations (Griffiths and Dillinger 1981). Onisimus litoralis and Gammarus setosus occupy intertidal or nearshore sublittoral habitats in the open water season (Dunbar 1954; MacGinitie 1955; Steele and Steele 1970; Thomson and Cross 1980; Cross 1982b).

Distributional and dietary information indicates that the ice habitat is important to amphipods during spring. However, the relative importance and seasonal utilization of pelagic, benthic and under-ice habitats by these species is not known. Although the abundance and biomass of nearshore amphipods have been reported for intertidal, sublittoral and under-ice habitats in the eastern Arctic, simultaneous sampling of under-ice and benthic substrates and consecutive sampling of one area through the season (i.e. under fast ice and during the open water season) have not been carried out.

Ice-associated invertebrates (copepods and amphipods) are important food items for arctic cod (Bain and Sekerak 1978; Bradstreet and Cross 1980, 1982; Craig et al. 1982), various marine birds (Bradstreet 1976, 1980; Divoky 1978; Johnson and Richardson 1981; Bradstreet and Cross 1982), and ringed seals (Finley 1978). In addition, the arctic cod is a major prey species of marine mammals and birds in the Canadian Arctic (Dunbar 1941, 1949; McLaren 1958; Bradstreet 1976, 1977, 1979, 1980, 1982; Finley 1976; Davis and Finley 1979; Finley and Gibb 1982, in press; Finley et al. 1982) and elsewhere. Thus, under-ice communities may be critical elements of arctic marine food webs. Damage to the under-ice communities could have effects on the mammals and birds that occupy the higher trophic levels of the food webs.

Studies of plant and animal communities inhabiting the undersurface of arctic sea-ice, and in particular studies allowing direct observations by use of SCUBA methods, have become a focus of attention only recently. To date, few quantitative studies of this type have been conducted. Recent reviews of published research on under-ice biota in the Arctic and Antarctic are given by Horner (1976, 1977). These include details of research carried out by a group from the University of Alaska who used surface-operated and SCUBA methods to study microalgae and primary productivity during 1972-1974. SCUBA-based quantitative studies of under-ice communities in the central and eastern parts of the Canadian Arctic are those of Buchanan et al. (1977), Thomson et al. (1978) and Cross (1980, 1982a,b).

In the event of a marine oil spill or blowout, large quantities of oil are most likely to accumulate in the under-ice, intertidal and shallow sublittoral habitats. Data on the effects of treated and untreated oil on the biota of these habitats would be of use in decisions regarding the use of chemical countermeasures for oil spills in ice-covered waters. Productivity and biomass of phytoplankton under oiled ice have been reported (e.g., Adams 1975), and laboratory experiments concerning effects of oil and dispersed oil on arctic phytoplankton have been carried out (e.g., Hsiao 1978). To our knowledge, the only previous study of oil effects on ice algae is that of Cross (1982b).

Oil effects on arctic meiofauna have not been studied, but this group has become a focus of pollution studies in recent years. Raffaelli and Mason (1981) and Warwick (1981a) have postulated that nematode to copepod ratios in meiobenthic communities could be potentially useful in the monitoring of pollution. Presumably, the ratio would increase in polluted areas because of greater availability of food to nematodes, and the greater sensitivity of copepods to pollutants (Bodin and Le Moal 1982; McLachlan and Harty 1982). Under-ice meiofaunal communities might be useful for oil spill monitoring in arctic regions where ice is present most of the year.

Laboratory studies concerning the acute toxicity of oil to arctic marine invertebrates have been conducted using animals from both the Beaufort Sea (Percy 1974, 1976, 1977a,b; Percy and Mullin 1975, 1977; Busdosh and Atlas 1977) and the eastern Arctic and sub-Arctic (Foy 1978, 1979). These studies have provided useful information on the relative sensitivities of a range of organisms, including some species of under-ice amphipods, but laboratory studies cannot be used to predict the effects of oil contamination in a natural field situation (Foy 1978, 1979). *In situ* studies of oil effects on nearshore arctic benthos were initiated in 1980 (Cross and Thomson 1981, 1982), but similar studies have not previously been carried out in arctic intertidal or under-ice habitats.

In the first year of this study, Cross (1982b) examined effects of *in situ* applications of oil and dispersed oil on under-ice algae and amphipods at Cape Hatt, Baffin Island, during May 1981. Oil and dispersed oil were added to chambers in the under-ice surface, productivity was measured, and the results were compared with those from simultaneous controls. Oil at low concentrations had little effect on productivity, but oil at the highest level tested caused significantly reduced uptake of radioactive carbon. Dispersed oil at the lowest level tested appeared to stimulate photosynthesis, but at the highest level there was near zero productivity. Distributions and population structures of under-ice and intertidal amphipods in the BIOS (Baffin Island Oil Spill Project) study bays were described. Data were collected prior to the experimental release of oil at Cape Hatt in August 1981, and the intertidal habitat was sampled again following the release of oil. Numbers of *Gammarus setosus* in the intertidal area of the surface oil release bay decreased by almost an order of magnitude, whereas those in Bays 9 and 10 (dispersed oil bays) decreased by 15 to 40%. These measured decreases were consistent with direct observations made during the oil releases.

The present study is a continuation of that of Cross (1982b). Distribution and life history data were collected for amphipods occupying under-ice, intertidal and shallow sublittoral habitats in the BIOS study bays one year after the release of oil. Similar data collected during 1981 (pre- and 2-4 weeks post-spill) are included in the present report. Productivity studies described herein address the effects of oil, solidified oil and dispersed oil (three different chemical dispersants) on productivity of ice algae and on associated variables, and also on meiofaunal communities. By using spatial and temporal controls we examine the initial impact on and subsequent recovery of under-ice communities subjected to a single application of these treatments.

MATERIALS AND METHODS

Field studies were carried out during 16-31 May, 10-19 August and 7-8 September 1981, and during 8 May - 2 June, 20-25 August and 6-11 September 1982 from the BIOS (Baffin Island Oil Spill) project base camp located at Cape Hatt, Baffin Island. The study area consisted of five shallow embayments in Ragged Channel, some 5-8 km SSE of Cape Hatt (72°27'N, 79°51'W). Bays 9 and 10 are shallow indentations in the coastline, each about 500 m in length, separated by the delta of a small stream and a distance of somewhat less than 500 m. Bays 13 and 7 are similar in size and configuration; the former is located about 3 km to the north and the latter is about 6 km to the south, and just south of another small stream. Bay 11 has been designated as the lower half of a deeper embayment approximately 1 km x 1 km in dimensions, located approximately 1 km north of Bay 10 (Fig. 1).

All under-ice and sublittoral sampling and experimental work was carried out by SCUBA divers working though holes in the ice (May) or from small inflatable boats (August and September). Studies on amphipod distribution and population structure were conducted in Bays 7, 9, 10 and 11 (Fig. 1), at a depth of 3-5 m or on the ice undersurface at the same locations. Intertidal sampling was carried out on the beach between two markers, 150 m apart, which demarcated the sampling locations within the BIOS study bays. Experimental studies on ice algae and meiofaunal communities were conducted on the under-ice surface in Bay 13 over a water depth of 10 m.

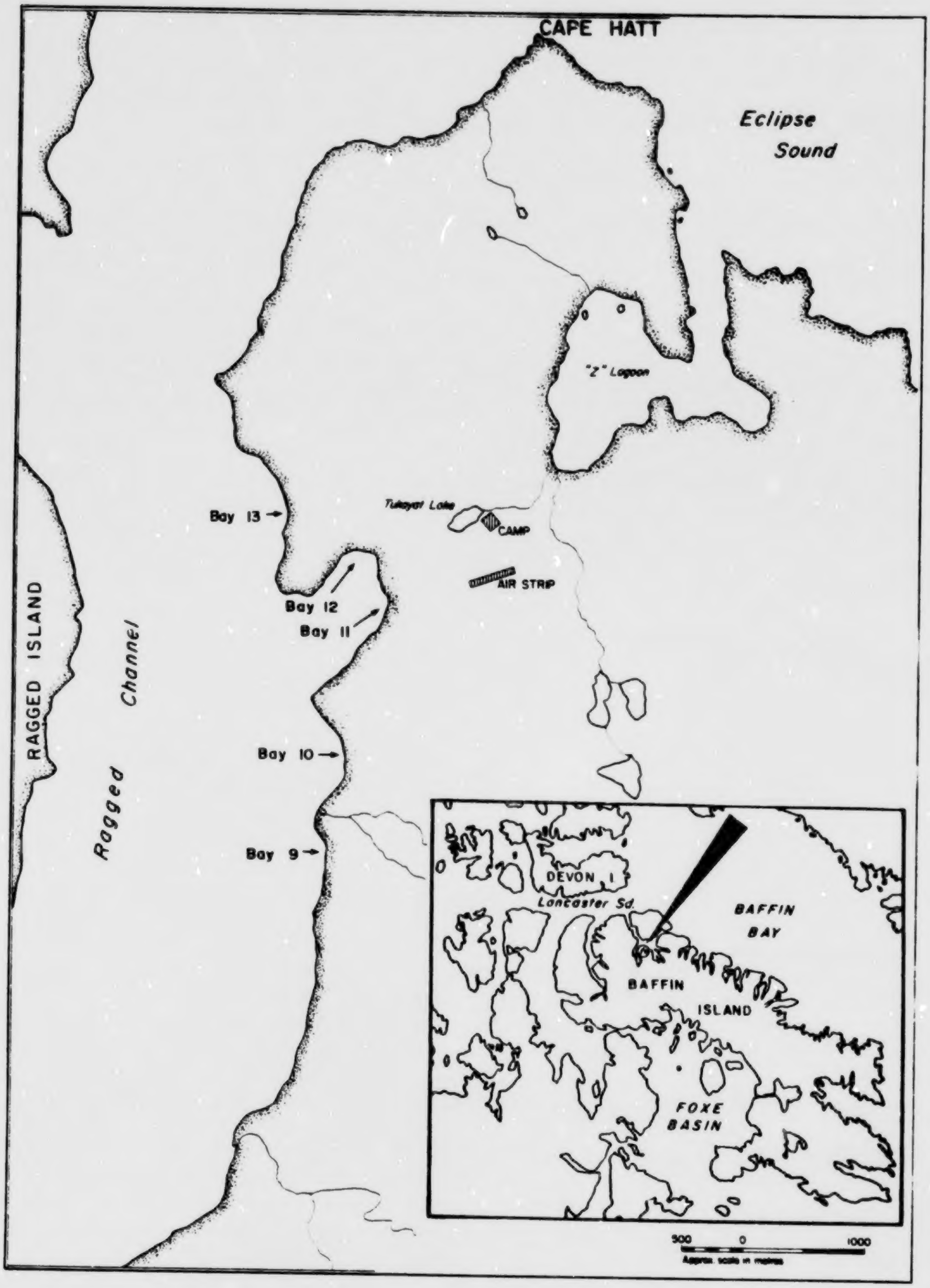
CAPE HATT
Eclipse
Sound
"Z" Lagoon
Tukayat Lake
CAMP
AIR STRIP
Bay 13
Bay 12
Bay 11
Bay 10
Bay 9
RAGGED ISLAND
Ragged Channel
DEVON I
Lancaster Sd.
BAFFIN
BAY
BAFFIN
ISLAND
FOXE
BASIN
500
0
1000
Approx. scale in metres

FIGURE 1. Locations of study bays at the BIOS project site at Cape Hatt, Baffin Island.

Amphipod Distributions and Population Structures

Quantitative samples of amphipods were collected in under-ice, intertidal and shallow (3-5 m) sublittoral habitats in each of BIOS study Bays 7, 9, 10 and 11 (Fig. 1). The under-ice surface was sampled during 17-19 May and 31 May 1981, and during 8-11 and 30-31 May 1982 (10-16 replicates per bay per time). The intertidal habitat was also sampled at two times in each year: during 17-19 August and on 7 September 1981, and during 20-24 August and 6-9 September 1982 (10 replicates). The shallow sublittoral habitat was sampled at three times in each year: during 17-19 May and on 10 August and 8 September 1981, and during 30-31 May, 21-25 August and 8-11 September 1982 (10 replicates). Sampling in Bay 7 was not carried out in May 1981. Sampling locations selected in 1981 were relocated as closely as possible in 1982.

In late August 1981, 15 m^3 of untreated Lagomedio oil was released within booms on the surface of Bay 11, and an additional 15 m^3 of the same oil treated with the dispersant Corexit 9527 (10 oil:1 Corexit) was released underwater in Bay 9 (Fig. 1). Currents carried the dispersed oil into Bay 10, which had originally been designated as the control bay. This resulted in a relatively high level of contamination of Bay 10--approximately one order of magnitude lower than that in the dispersed oil release bay. For several days following the dispersed oil release, low levels of oil (average maximum of 50 ppb) were also found in the new control bay--Bay 7--and also throughout Ragged Channel (Fig. 1).

All systematic sampling on the under-ice surface was at least 5 m from the entry hole to avoid disturbance artifacts. Macrofauna (mainly amphipods) on the under-ice surface were sampled by scraping fine mesh (1 mm) dip nets with a 40 cm flat top for 10 m distances along the under-ice surface in areas not previously disturbed by respired SCUBA air. These 10 m transects extended radially from the entry hole (5-15 m, 15-25 m) and were relatively evenly distributed in the semi-circle seaward of the hole. Entry holes were located just seaward of major tide cracks, and the area sampled consisted only of relatively flat, smooth ice. Meiofauna and microalgae were sampled only in 1982. Meiofauna were collected with 10 cm diameter plexiglass chambers inserted 2-3 cm into the soft ice, and microalgae were collected with 2.5 cm diameter stainless steel corers driven 10 cm into the ice (5 replicates of each type of core per bay per time).

Intertidal sampling was carried out at or near low tide. A 0.25 m^2 aluminum quadrat was placed in the water with its shoreward edge 0.5 m seaward from the water line, the substrate was manually disturbed, and all of the enclosed animals were removed by using a small aquarium net. Sampling locations were randomly selected along 150 m segments of the bays that corresponded with the benthic transects sampled during the BIOS study. Substrates consisted of mixed sand, pebble and cobble.

Sublittoral sampling was carried out using a self-contained diver-operated airlift. The airlift consisted of a weighted length of pipe 8 cm in diameter fitted at the top with a 1 mm mesh net, which retained the sample and could be removed quickly and capped. Air was supplied from a 20 MPa air cylinder fitted with the first stage of a diving regulator which reduced air pressure to approximately 860 kPa above ambient. Areas to be sampled were demarcated by an aluminum ring containing an area of 0.15 m^2. Motile epibenthos within the 0.15 m^2 area were contained, and those outside were excluded, by 1 mm mesh netting covering the top of each ring. The netting over each ring contained a capped central receptacle to receive the 'mouth' of the airlift.

The airlift frame was placed on the bottom and pushed as far as possible into the substrate to contain shallow infauna. The airlift was attached to the net, the air was turned on, and the mouth of the airlift was moved around to cover thoroughly the area within the ring. The net on the airlift was then removed, capped and replaced.

In May, sublittoral sampling locations were randomly selected at a depth of 3-5 m within an area on the bottom below the under-ice sampling area. In August and September, samples of epibenthic and shallow infaunal amphipods were again collected at the same depths. In 1981, these areas only approximately corresponded to those sampled in May, whereas in 1982 locations were marked in May and relocated in August and September. The substrate consisted of coarse to fine sand with pebbles and cobble (up to 10 cm); data on substrates in Bays 9, 10 and 11 were reported by Cross and Thomson (1981).

All samples were preserved in 10% formalin. Amphipods were identified, counted and weighed at species level (whenever possible) and amphipod lengths were measured to the nearest mm. Amphipods of the genus Onisimus were not identified to species if <6 mm long; most Ischyrocerus collected were damaged and hence were only identified to generic level. Wet weights of each species or group in each sample were obtained by gently blotting dry and weighing on a Mettler PT200 balance to the nearest milligram. Amphipods were transferred to a solution of 3% propylene glycol in 75% ethanol for storage.

The resulting data were analyzed with one- and two-factor analyses of variance, using the SAS general linear models (GLM) program (Helwig and Council 1979). Variables analyzed included abundance (nos./m^2) and biomass (mg/m^2) of all amphipods and of dominant species. All data were log-transformed prior to analysis.

Primary Productivity of Ice Algae and Meiofaunal Communities

The effects of treated and untreated oil on under-ice communities were studied during 14 May-2 June 1982 in Bay 13 (Fig. 1). The treatments were crude oil (Venezuela Lagomedio), solidified oil (BP treatment), oil dispersed with three different chemical dispersants (Corexit 9527, BP1100 WD and BP CTD), and no oil (control). Each of these treatments was applied to the under-ice surface within large buoyant plexiglass enclosures 1.2 m in diameter and 30 cm in depth. There were two enclosures for each of the six treatments; one set of six enclosures was established at Location 1 and the other set of six was nearby at Location 2.

Oil and dispersants (10:1 ratio) were mixed with seawater in 9 L air-pressurized hand-held fire extinguishers. Dispersed oil, untreated oil, and water (control and solidified oil treatments) were introduced from the extinguishers into the enclosures. In this way, any disturbance of the under-ice surface that resulted from the use of fire extinguishers was similar for all treatments. Oil was solidified under ambient (surface) conditions, transferred to a polyethylene bag and passively introduced into the enclosure. The bottom of each enclosure was covered by polyethylene sheeting during the application of treatments. Dispersed oil was contained within the enclosures for a period of 4-5 h and then the bottom sheet was removed; control, oil and solidified oil enclosures remained covered during the release of the dispersed oil. Untreated oil and solidified oil remained in localized areas within the enclosures throughout the study. Just after the treatments were applied, water samples from each enclosure were collected in 50 mL polypropylene syringes and frozen. Oil concentrations were measured with a Turner-Designs Fluorometer by Seakem Oceanography Ltd. The nominal concentration within each dispersed oil enclosure was 100 ppm; actual concentrations in the enclosures (average ppm in two samples) were as follows:

	Treatment					
	Control	Oil	Solidified Oil	BP CTD +Oil	BP 1100WD +Oil	Corexit 9527 +Oil
Location 1	0.24	0.19	0.15	5.80	15.50	14.50
Location 2	0.28	0.22	0.15	6.70	26.50	36.50

Sampling was carried out within the enclosures during five periods, each consisting of two days: 18-19, 21-22, 26-27, 28-29 May and 1-2 June. Treatments were applied on 23-24 May. In each of these periods, Locations 1 and 2 were sampled (or treated) on the first and second day, respectively.

Productivity of under-ice algae was determined by a modification of the standard ^{14}C light and dark bottle technique (Strickland and Parsons 1972). The 'bottles' in this case were cylindrical plexiglass chambers with an area of 78.6 cm^2 and a length of 15.3 cm (volume = 1202 cc). Chambers were inserted about 1-2 cm into the soft bottom layer of ice, and ^{14}C-sodium bicarbonate (New England Nuclear Corp.) with a specific activity of 53 µCi/mol was injected to yield a final concentration of 75.9 µCi/L. Incubations began between 1100 and 1200 h (local apparent) and were allowed to proceed for a period of 2-2.5 hours. At the end of the incubation periods, ice cores were severed, the chambers were capped and 1 mL of concentrated formalin was injected into each.

During each sampling period, three replicate light chambers and one dark chamber were used to incubate ice (+ water) samples in each enclosure. Because each treatment was applied to two enclosures, there was a total of six light and two dark chambers per treatment and sampling period. In order to determine the contribution of algae in the water to the above results, water samples were also collected immediately beneath the ice within the enclosures. One light and one dark chamber were incubated for each treatment in each period. Separate samples of ice (+ water) were collected in the same way and returned immediately to the field laboratory for the determination of salinity, alkalinity, and ambient inorganic nutrient concentrations.

Carbonate alkalinity was calculated according to the methods of Strickland and Parsons (1972). A Fisher Accumet pH meter (model 630, accuracy ± 0.02 pH) was used to measure pH, and salinity was calculated from Knudsen tables using temperature and specific gravity measurements obtained with a hydrometer (Fisher, 1.000-1.070). A recording pyranometer (Kipp and Zonen, model CM-6) located at the Cape Hatt base camp recorded incoming radiation (W/m^2) during the four weeks that the camp was occupied.

Light was measured with an underwater irradiometer (Kahlsico model 268 WA310) below the layer of ice algae and above the algal layer (after scraping this layer away) in each enclosure at the beginning and end of each incubation. Simultaneous measurements above the ice were made with a surface cell so that percent transmission through the ice could be calculated.

Incubation chambers were returned to the field laboratory immediately after the incubation period and processed within 8 h. Actual sample volumes varied to a maximum of 1350 mL and were sometimes very low because chambers leaked during transport to the laboratory. Data from chambers where actual volume was <1100 mL (26 of 240 ice samples; 13 of 60 water samples) were not included in the analyses. The nominal chamber volume of 1200 mL was used in calculations for all chambers. Subsampling and filtering procedures are shown in Figure 2 and numbers of samples are given in Appendix A. Filtrations were carried out at vacuum pressures of 120 mm Hg (dissolved organic carbon samples) or 200 mm Hg (all other samples).

Nutrient samples were preserved with 1 or 2 drops of chloroform (samples for phosphate and ammonium analyses) or 2 drops of concentrated sulphuric acid (samples for nitrate-nitrite analysis) before freezing. Orthophosphate (PO_4) and nitrate (NO_3) concentrations were determined on thawed samples using a Technicon Auto-Analyzer II continuous flow system and standard Technicon analysis procedures. Ammonia (NH_3) concentrations were determined

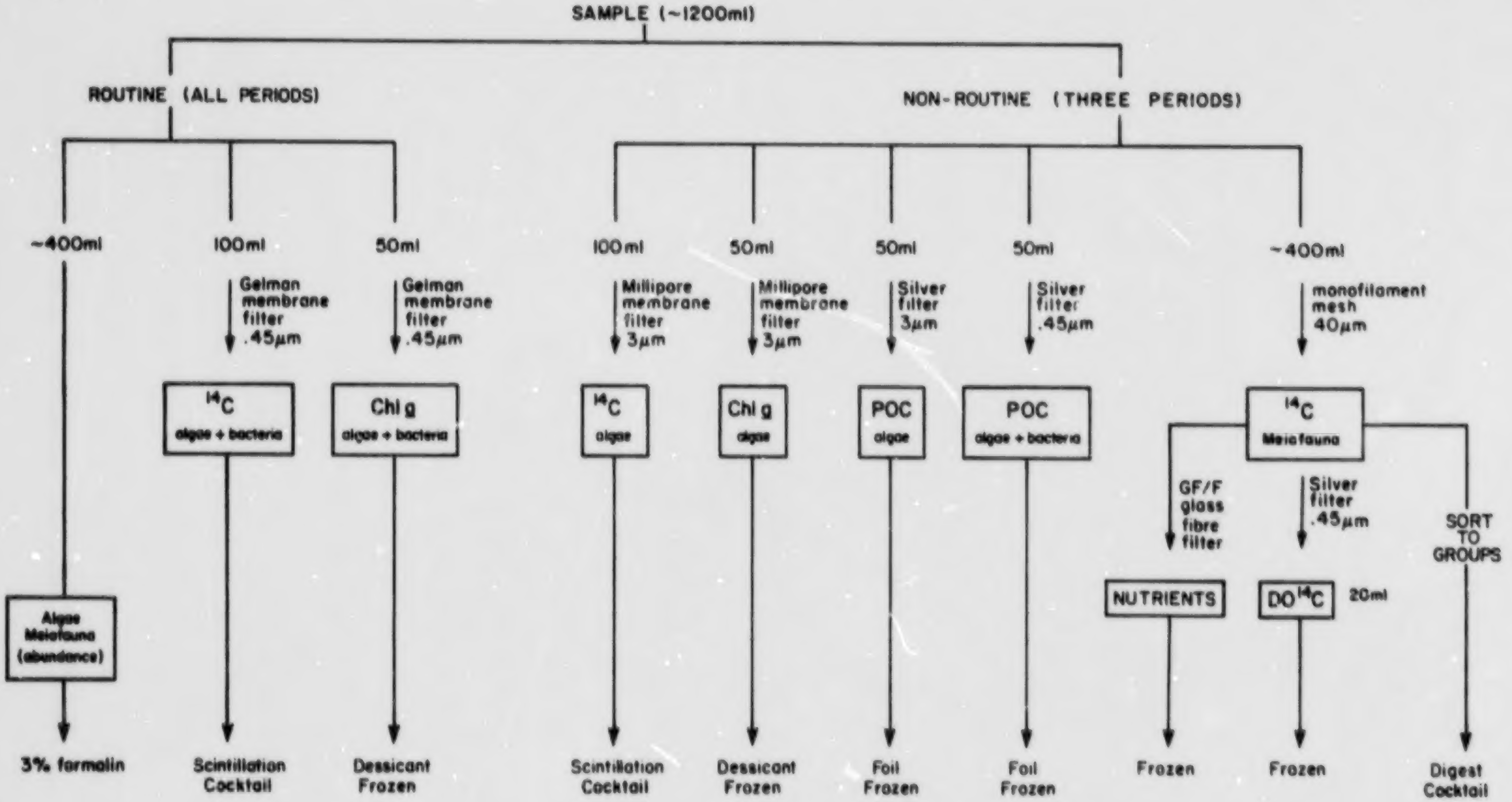
SAMPLE (~1200ml)
ROUTINE (ALL PERIODS)
NON-ROUTINE (THREE PERIODS)
~400ml
100ml
50ml
100ml
50ml
50ml
50ml
~400ml
Gelman membrane filter .45µm
Gelman membrane filter .45µm
Millipore membrane filter 3µm
Millipore membrane filter 3µm
Silver filter 3µm
Silver filter .45µm
monofilament mesh 40µm
Algae Meiofauna (abundance)
14C algae + bacteria
Chl a algae + bacteria
14C algae
Chl a algae
POC algae
POC algae + bacteria
14C Meiofauna
GF/F glass fibre filter
Silver filter .45µm
SORT TO GROUPS
NUTRIENTS
DO14C
20ml
3% formalin
Scintillation Cocktail
Dessicant Frozen
Scintillation Cocktail
Dessicant Frozen
Foil Frozen
Foil Frozen
Frozen
Frozen
Digest Cocktail

FIGURE 2. Representation of techniques for subsampling, filtration and preservation of ice and water samples.

according to the procedures of Dal Pont et al. (1974). All nutrient concentrations were determined at the Arctic Biological Station, Ste-Anne-de-Bellevue, Quebec.

Chlorophyll a was measured at the Arctic Biological Station by the spectrophotometric procedure described in Strickland and Parsons (1972) using the equation of Jeffrey and Humphrey (1975). Particulate organic carbon concentrations were determined at the Arctic Biological Station by the method described in Bunch et al. (1981).

All radiometric procedures including the preparation of stock solutions were conducted at the Arctic Biological Station. To determine productivity, ^{14}C radioactivity was measured using a Nuclear Chicago Isocap 300 scintillation counter. Meiofauna were sorted into major taxa and processed as described in the NEN-LSC Applications Notes (#1-30) prior to the measurement of radioactive carbon. Radioactivity in dissolved organic carbon was measured by scintillation counting of the ^{14}C organic residue after acidification to pH 2 and removal of $H^{14}CO_3$ in a gas stream (N_2, 30 min.).

Microalgae (subsamples of 5 mL) were identified and enumerated using a modification of the inverted microscope method of Utermohl (1958) and magnifications to 625X. Normally, 2.5-10% of the settling chamber was scanned for abundant species and 50% was scanned for others. Numbers of ice algae enumerated were converted to cells/L. Each diatom, dinoflagellate and Dinobryon cell was counted as an individual, whereas each colony (except for Dinobryon) and filament of other groups was counted as one individual. Microalgae were identified to species whenever possible. References for identification included Cupp (1943), Cleve-Euler (1951-5) and Hendey (1964) for diatoms, and Paulsen (1908) and Lebour (1925) for dinoflagellates.

Meiofaunal analysis was based on subsamples (approximately 500 mL) from each chamber, preserved in 5% formalin and filtered through 40 um mesh netting to reduce the volume. Major taxonomic groups (copepods, nematodes and polychaetes) in each sample were enumerated using a binocular microscope and plankton counting wheel. Copepods in one half of the total number of samples were identified to species level and counted.

Data on ice algae and meiofauna were analyzed with two- and three-factor analyses of variance, using the SAS general linear models (GLM) program (Helwig and Council 1979). Variables analyzed included productivity, chlorophyll _a_, microalgal and meiofaunal densities, and ratios between productivity, chlorophyll _a_, percent transmission and _in situ_ light. Differences between filter types (0.45 µm and 3.0 µm cellulose acetate filters) in productivity, chlorophyll _a_ and particulate organic carbon were analyzed with t-tests for paired comparisons (Sokal and Rohlf 1969).

RESULTS AND DISCUSSION

Amphipod Distributions and Population Structures

Site Description

Under-ice amphipods were sampled over a water depth of 3-4 m in Bays 7, 9, 10 and 11 at Cape Hatt (Fig. 1). Bays 9-11 were sampled in both 1981 and 1982; Bay 7 was sampled only in 1982. Ice depths at the dive holes were 122 to 163 cm in 1981 and 110 to 142 cm in 1982. Snow depths (cm) in each bay in each year were as follows:

	Snow depth--mean ± SD (n)			
	Bay 7	Bay 9	Bay 10	Bay 11
31 May 1981	-	14.3 ± 4.2 (39)	14.3 ± 4.9 (27)	8.9 ± 5.5 (39)
11,12 May 1982	23.8 ± 4.1 (17)	18.7 ± 4.9 (20)	10.6 ± 2.5 (20)	17.0 ± 6.2 (20)
3 June 1982	20.8 ± 3.9 (21)	21.9 ± 5.0 (20)	8.8 ± 2.6 (20)	19.0 ± 9.2 (20)

The bottom of the ice was soft and granular in texture, with small hummocks, depressions and ridges several metres across and up to 20 or 30 cm in relief. In each bay a relatively light-coloured algal layer was present on the ice under-surface, and its distribution was patchy on a scale of metres or tens of metres.

Intertidal and shallow sublittoral substrates consisted of fine to coarse sand mixed with pebble and cobble; finer sediments became increasingly predominant with increasing depth. The shoreline was icebound to a depth of 2 or 3 m during May, and very little drifting or grounded ice was present during August and September of either 1981 or 1982.

The under-ice macrofauna in the three study bays included arctic cod (*Boreogadus saida*) and mysids (*Mysis* spp.), but otherwise consisted entirely of gammarid amphipods. Cod were observed only in the large tide cracks just inshore of the entry holes in each of the bays. The edges of these cracks were rounded and about 1/2 m apart at the bottom, and only a few cm wide at a distance of about 1/2 m from the bottom of the ice; most cod moved up into the cracks when disturbed. Mysids were present throughout the water column in each bay, and were generally concentrated in the first metre of water just below the ice. Densities of mysids were extremely variable both within and among bays; estimates based on amphipod dip net samples were as high as 585 individuals/m^2 or 16 g/m^2. These are underestimates, probably by at least an order of magnitude, because our nets sampled only a part of the water column and because mysids actively avoided the nets. The following results concern only the amphipods collected in this study, and only those amphipods occurring on the under-ice surface are treated in detail.

Species Composition

Thirteen species of gammarid amphipods were collected on the under-ice surface at Cape Hatt in 1982 (Table 1). Ten species were collected in 1981 (Cross 1982b), of which eight were also present in 1982. Four of the species collected only in 1982 (Stenothoidae sp., *Pleusymtes* sp., *Monoculodes*

Table 1. Species composition of amphipods in under-ice, intertidal and sublittoral habitats in four bays[1] at Cape Hatt, Baffin Island, during May, August and September 1982[2].

Taxon	Under-ice (May)			Intertidal (August-September)			Sublittoral (May, August, September)		
	% of numbers	% of biomass	% occurrence	% of numbers	% of biomass	% occurrence	% of numbers	% of biomass	% occurrence
Gammaridae									
Gammaracanthus loricatus	0.3	5.6	11.7	0.2	0.6	21.3	-	-	-
Gammarus setosus	1.9	27.4	39.8	43.8	66.1	97.5	<0.1	<0.1	0.8
Gammarus wilkitzkii	-	-	-	<0.1	0.1	6.3	-	-	-
Melita dentata	-	-	-	-	-	-	<0.1	0.1	0.8
Weyprechtia pinguis	10.7	36.8	84.4	-	-	-	0.4	2.8	11.8
Lysianassidae									
Anonyx nugax	<0.1	0.1	1.6	-	-	-	0.8	31.6	33.6
Anonyx sarsi	-	-	-	<0.1	0.2	3.8	0.2	8.1	14.3
Anonyx juveniles	-	-	-	0.2	0.1	17.5	1.1	1.4	29.4
Boeckosimus edwardsi	-	-	-	<0.1	<0.1	1.3	-	-	-
Boeckosimus plautus	-	-	-	0.1	0.1	13.8	0.9	1.8	25.2
Boeckosimus sextonae	-	-	-	<0.1	<0.1	1.3	-	-	-
Onisimus glacialis	1.5	1.4	28.9	20.9	12.2	81.3	<0.1	<0.1	0.8
Onisimus litoralis	0.4	4.4	19.5	21.6	17.4	90.0	0.1	0.2	5.0
Onisimus juveniles	57.7	17.3	92.2	0.1	<0.1	8.8	<0.1	<0.1	1.7
Orchomene minuta	-	-	-	0.4	0.2	32.5	15.9	15.0	58.0
Ischyroceridae									
Ischyrocerus sp.	24.2	6.0	85.2	<0.1	<0.1	1.3	1.4	0.8	14.3
Calliopiidae									
Apherusa glacialis	0.2	0.1	9.4	-	-	-	0.1	<0.1	1.7
Apherusa megalops	-	-	-	0.1	<0.1	20.0	11.2	2.0	37.8
Stenothoidae									
Unidentified spp.	<0.1	<0.1	0.8	<0.1	<0.1	1.3	7.1	1.1	48.7
Pontogeneiidae									
Pontogeneia inermis	<0.1	<0.1	0.8	-	-	-	0.4	0.4	6.7
Pleustidae									
Pleusymtes sp.	0.1	<0.1	3.9	-	-	-	4.5	0.8	26.1
Oedicerotidae									
Bathymedon longimanus	-	-	-	-	-	-	<0.1	<0.1	0.8
Bathymedon obtusifrons	-	-	-	-	-	-	3.1	0.7	40.3
Monoculodes latimanus	<0.1	<0.1	0.8	-	-	-	5.3	4.4	50.4
Monoculodes packardi	-	-	-	7.5	0.3	51.3	-	-	-
Monoculodes spp.[3]	-	-	-	-	-	-	1.5	1.8	31.9
Monoculopsis longicornis	-	-	-	0.3	<0.1	27.5	<0.1	<0.1	3.4
Paroediceros lynceus	-	-	-	-	-	-	2.1	8.0	41.2
Westwoodilla megalops	-	-	-	-	-	-	0.4	0.1	9.2
Dexaminidae									
Guernea sp.	<0.1	<0.1	0.8	<0.1	<0.1	1.3	35.8	5.7	90.8
Haustoriidae									
Pontoporeia affinis	-	-	-	<0.1	<0.1	3.8	-	-	-
Pontoporeia femorata	-	-	-	<0.1	<0.1	2.5	4.3	9.8	56.3
Corophiidae									
Corophium clarencense	-	-	-	-	-	-	0.4	0.1	8.4
Protomedia fasciata	-	-	-	-	-	-	1.1	0.4	16.0
Phoxocephalidae									
Harpina serrata	-	-	-	-	-	-	<0.1	<0.1	0.8
Phoxocephalus holbolli	-	-	-	-	-	-	<0.1	<0.1	1.7
Atylidae									
Atylus carinatus	-	-	-	-	-	-	<0.1	0.1	2.5
Ampeliscidae									
Ampelisca macrocephala	-	-	-	-	-	-	<0.1	<0.1	0.8
Total %[4]	97.0	99.1		95.2	97.3		98.1	97.2	
Total number, biomass (g) or n	7,117	52.835	128	19,416	260.795	80	9,165	30.429	119
Total nos./m^2 or g/m^2	14	0.103		971	13.040		509	1.691	

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Oil was released in late August 1981.

[3] Includes *Monoculodes borealis*, *M. kroyeri* and *M. schneideri*.

[4] Does not include unidentified, damaged or some juvenile amphipods.

latimanus and *Guernea* sp.) have not previously been collected on the under-ice surface; none of these species accounted for more than 0.1% of total numbers collected. Nine of the 15 species found at Cape Hatt in the two years have previously been collected in spring on the under-ice surface at various localities in the central and eastern Arctic (Green and Steele 1975; Thomson et al. 1975; Buchanan et al. 1977; Thomson et al. 1978; Cross 1980, 1982a). Another two species, *Weyprechtia pinguis* and *Pontogeneia inermis*, have previously been collected on the under-ice surface only in late February in the western Arctic (Griffiths and Dillinger 1981).

During May 1982, *Onisimus* juveniles were the dominant amphipods on the under-ice surface in terms of numbers (57.7%). Two species, *Weyprechtia pinguis* and *Ischyrocerus* sp., together accounted for most of the remaining numbers (34.9%). Three taxa, *Weyprechtia pinguis*, *Gammarus setosus* and *Onisimus* juveniles, together accounted for 81.5% of total biomass. Percent composition was similar to this in 1981, except that *Onisimus* juveniles were much less important (only 1.0% of numbers, 0.3% of biomass). *Ischyrocerus* sp. and *Weyprechtia pinguis* were dominant in 1981 (together comprising 61.9% of numbers) and the ratio between the two (~2:1) was the same in both years. *Weyprechtia pinguis*, *Gammarus setosus* and *Onisimus litoralis* accounted for most (81.5%) of the biomass in 1981 (Cross 1982b).

Elsewhere, species of *Onisimus* or *Gammarus* have most often been reported to be the dominant (or the only) amphipods on the under-ice surface (Green and Steele 1975; Buchanan et al. 1977; Thomson et al. 1978; Grainger and Hsiao 1982). *Ischyrocerus* sp. was also dominant at some offshore stations in Pond Inlet (Cross 1980, 1982a), but *Weyprechtia pinguis* has not been reported to be dominant elsewhere.

Eighteen species of gammarid amphipods were found in the intertidal habitat in August-September 1982 (Table 1). *Gammarus setosus* was dominant in terms of both numbers (43.8% of total) and biomass (66.1% of total). *Onisimus litoralis* and *Onisimus glacialis*, in approximately equal proportions, together comprised most of the remaining numbers and biomass (42.5 and 29.6%, respectively). *Gammarus setosus* was also dominant in 1981 intertidal samples from Cape Hatt, but many fewer species were collected in 1981; *Onisimus glacialis* was notable in its absence (Cross 1982b). This is likely a result of sampling at lower tide levels in the second year (see below).

A much higher number of species was found in the shallow (3-4 m) sublittoral habitat in both years: 33 in 1982 (Table 2) and 38 in 1981 (Cross 1982b). Dominant species were also similar in both years. *Guernea* sp., *Orchomene minuta* and *Apherusa megalops* together comprised 62.9% of total numbers in 1982 and *Guernea* sp., *Orchomene minuta* and *Protomedia fasciata* comprised 50.7% of numbers collected in 1981. *Anonyx nugax*, *Anonyx sarsi* and *Orchomene minuta* were dominant in terms of biomass in both years, together accounting for 56.0 and 54.7% of total biomass in 1981 and 1982, respectively.

None of the amphipod species found on the under-ice surface in 1982 was unique to this habitat. *Apherusa glacialis* was the only species collected only in May (Table 2). It formed a small part of the under-ice community and also was present in shallow sublittoral habitat. It was found in neither intertidal nor sublittoral habitats at any time in 1981 (Cross 1982b; Cross and Thomson 1982). This species is pelagic (Dunbar 1954) and often

Table 2. Percent contribution of under-ice amphipods to numbers collected in under-ice, intertidal and sublittoral habitats in four bays[1] at Cape Hatt, Baffin Island, during May, August and September 1982[2].

Taxon	Under-ice % of total numbers		Intertidal % of total numbers		Sublittoral % of total numbers		
	Early May	Late May	August	September	May	August	September
Onisimus juveniles	56.3	58.5	0.2	<0.1	<0.1	-	<0.1
Ischyrocerus sp.	25.9	23.0	-	<0.1	1.0	0.5	2.9
Weyprechtia pinguis	10.8	10.6	-	-	-	1.2	0.2
Gammarus setosus	1.5	2.2	52.8	37.7	<0.1	-	-
Onisimus glacialis	0.6	2.1	24.3	18.7	-	-	<0.1
Onisimus litoralis	0.8	0.2	8.1	30.8	0.1	0.1	0.1
Gammarus juveniles	0.2	0.6	<0.1	-	-	0.1	-
Gammaracanthus loricatus	0.3	0.3	0.2	0.1	-	-	-
Apherusa glacialis	0.3	0.1	-	-	0.3	-	-
Pleusymtes sp.	0.1	<0.1	-	-	1.2	6.1	7.5
Guernea sp.	-	<0.1	-	<0.1	34.1	42.8	31.8
Stenothoidae sp.	-	<0.1	-	<0.1	2.3	14.2	7.2
Monoculodes latimanus	<0.1	-	-	-	8.9	2.8	2.5
Anonyx nugax	-	<0.1	-	-	0.3	0.7	1.5
Pontogeneia inermis	-	<0.1	-	-	-	0.1	1.1
Total %	96.8[3]	97.6[3]	85.6	87.3	48.2	68.6	54.8
Total number collected	2854	4263	7813	11,603	3848	2479	2838
Total area sampled (m^2)	256	256	10	10	6	6	6

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Oil was released in late August 1981.

[3] Does not include unidentified and damaged amphipods.

associates with pan ice in late summer (Stephensen 1942; MacGinitie 1955; Divoky 1978; Thomson et al. 1978).

All of the other species that were common on the under-ice surface were clearly of benthic origin. Gammarus setosus, Onisimus litoralis and Onisimus glacialis almost exclusively inhabited intertidal areas during the ice-free season; this may also be true for Gammaracanthus loricatus, but numbers collected at any time were few. Weyprechtia pinguis and Ischyrocerus sp., on the other hand, were more common in sublittoral than in intertidal habitats during summer. In May, the former was present only on the under-ice surface, whereas Ischyrocerus sp. appeared to show little preference for either habitat. Habitat preferences apparently vary among species, localities and years. The distributions of Weyprechtia pinguis among habitats and months were similar in Cape Hatt in 1981 and 1982. However in 1981, unlike 1982, Ischyrocerus sp. was found in the sublittoral habitat only in May and even then was very rare (1 individual collected; Cross 1982b).

Percy (1975) reported that most Boeckosimus affinis congregate near the ice in winter, but some individuals remain in the sediment; the former animals leave the ice in late May and return to the bottom. Griffiths and Dillinger (1981) reported that Weyprechtia pinguis was collected both on the bottom and on the under-ice surface in Prudhoe Bay in late February.

Six species that were very rare on the under-ice surface in 1982 together comprised a large percentage of the amphipods collected in the sublittoral habitat (46.8 to 66.7%, depending on month). With the possible exception of Pontogeneia inermis, their occasional presence on the under-ice surface was likely due to chance.

Abundance and Biomass

Under-ice Habitat

Spatial Effects.--Direct observations by the divers indicated that the distribution of amphipods on the under-ice surface in all bays was patchy. Larger amphipod species (e.g. Gammarus setosus and Gammaracanthus loricatus) were often associated with brine channels and stalactites on the under-ice surface, or with the tide cracks located just inshore of each dive hole. Smaller amphipods were also patchily distributed and were apparently concentrated in areas where concentrations of ice algae were relatively high. The latter type of patchiness was the predominant type in our sampling locations. No systematic sampling was carried out in or near tide cracks, and neither stalactites nor large brine channels were common in the study area. The influence of a freshwater layer caused by melting ice in June and July has also been reported to affect amphipod distributions in Eclipse Sound, both in offshore areas (Cross 1980, 1982a) and at Cape Hatt (N. Snow, pers. comm.). No freshwater layer was observed in the study bays in either year, nor was surface melt apparent at the end of May in either year.

The observed patchiness is also evident in our data. For most species, bays and times, standard deviations greatly exceeded the means (Appendices B and C). Variability among bays is considered significant only if it is even more extreme than the within-bay variability.

Among-bay differences in the densities of dominant amphipod species were evident during each year. Three bays were compared in 1981 and four bays in 1982; analyses were carried out only for species and years with relatively high numbers of amphipods (Table 3). Densities of amphipods differed significantly among bays in the cases of Weyprechtia pinguis, Ischyrocerus sp. and total amphipods in both years, and Onisimus juveniles in 1982. Weyprechtia pinguis was least abundant in Bay 11 in both years, whereas Ischyrocerus sp. was most abundant in Bays 10 and 11 (Fig. 3). Onisimus juveniles were not common in any bay in 1981; in 1982 they were most abundant in Bay 10 and least abundant in Bays 9 and 11 (Fig. 4). In general, Bay 9 supported the lowest amphipod densities in both years. Highest amphipod densities occurred in Bay 11 in 1981, and in Bay 10 in 1982. This shift was primarily a result of decreases in Ischyrocerus sp. and Gammarus setosus densities from 1981 to 1982 in Bay 11, and increases in Onisimus juvenile densities from 1981 to 1982 in Bay 10 (Fig. 4).

Significant interactions between bay and month factors precluded interpretation of among-bay bay differences in densities of Gammarus setosus (1981 and 1982) and Onisimus litoralis (1981) (Table 3). Inspection of the data, however, shows clear among-bay differences (Fig. 3 and 4). Gammarus setosus was most abundant in Bay 11 and least abundant in Bay 9 during both years, and the opposite was true in the case of Onisimus litoralis in 1981. The latter species was rare in all but Bay 7 in 1982.

Thus there were pronounced among bay differences in abundances of amphipods on the under-ice surface. Analyses of variance and inspection of the data showed that each of the dominant species was more abundant in some

Table 3. Seasonal comparisons of the densities of amphipods on the under-ice surface in three or four bays[1] at Cape Hatt, Baffin Island during early and late May 1981 and 1982[2]. F-values are shown with significance levels (ns = $P>0.05$; * $P<0.05$; ** $P<0.01$; *** $P<0.001$). Significance levels are not shown for the main effects when the interaction term was significant.

Taxon/df	Comparison	Source of Variation		
		Bay[1]	Period[2]	Bay x Period
Gammarus setosus	1981	65.35	25.49	6.89 **
	1982	24.84	8.63	14.15 ***
Onisimus litoralis	1981	21.23	13.24	12.37 ***
Onisimus juveniles	1982	53.11 ***	20.06 ***	2.54 ns
Weyprechtia pinguis	1981	5.70 **	14.48 ***	2.17 ns
	1982	23.29 ***	3.03 ns	0.77 ns
Ischyrocerus sp.	1981	23.19 ***	6.91 *	0.24 ns
	1982	86.26 ***	2.43 ns	1.57 ns
Amphipoda (density)	1981	9.38 ***	23.24 ***	1.96 ns
	1982	36.85 ***	22.00 ***	1.69 ns
Amphipoda (biomass)	1981	2.16	14.92	6.73 **
	1982	1.91	7.65	3.75 *
Degrees of freedom	1981	2,74	1,74	2,74
	1982	3,120	1,120	3,120

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[1] Bays 9 (dispersed oil release), 10 (dispersed oil contamination) and 11 (surface oil release) in 1981; Bays 7 (reference), 9, 10 and 11 in 1982.

[2] 17-19 May and 31 May in 1981 (Pre-spill); 8-11 May and 30-31 May in 1982 (Post-spill).

[3] Duncan's Multiple Range Test, $\alpha = .05$.

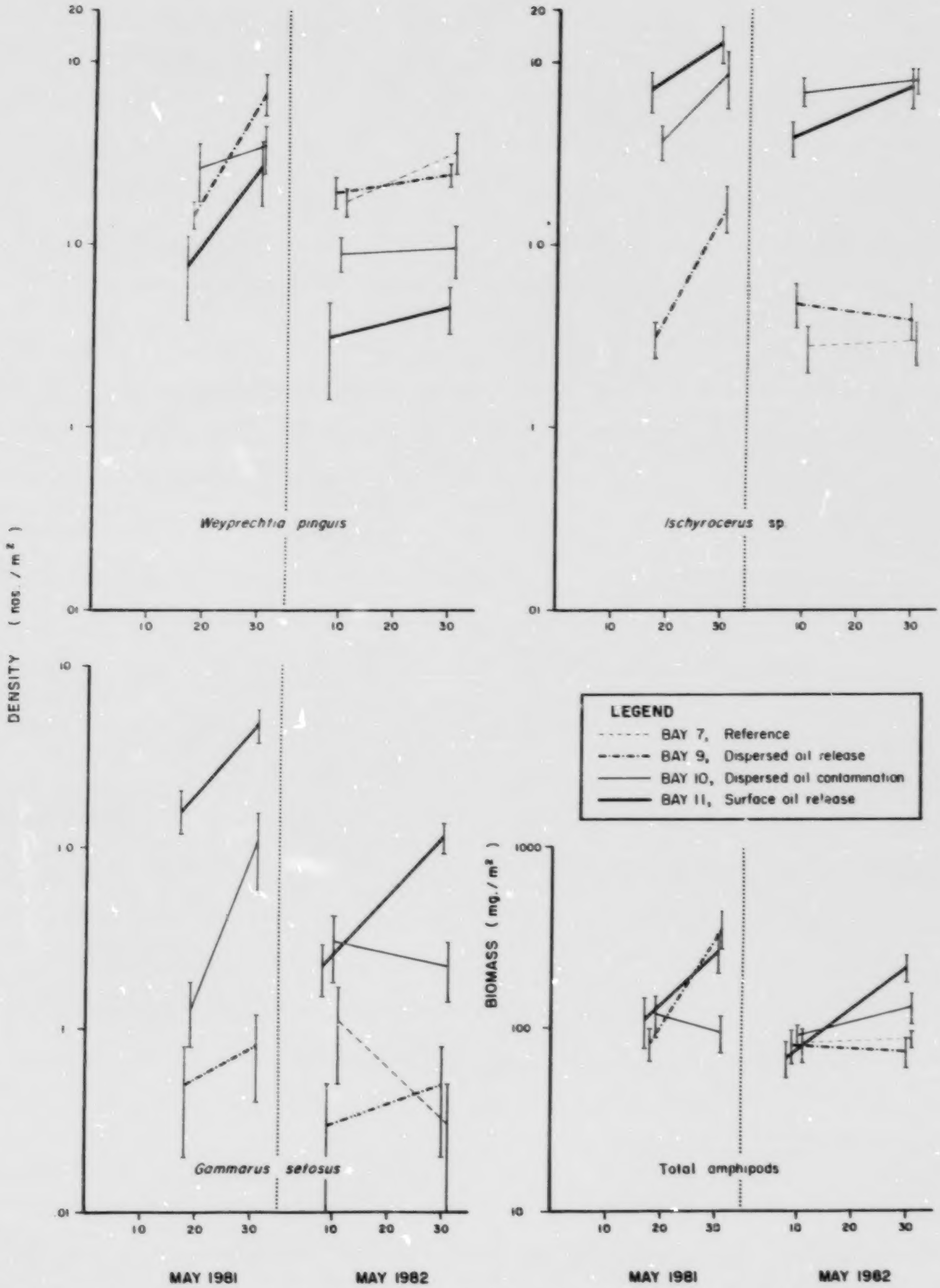

FIGURE 3. Densities of three amphipod species and biomass of total amphipods in the under-ice habitats of four bays at Cape Hatt, Baffin Island, during May 1981 (pre-spill) and May 1982 (post-spill). Data are expressed as the mean of 10-16 replicate 4 m^2 net samples; vertical lines show standard error.

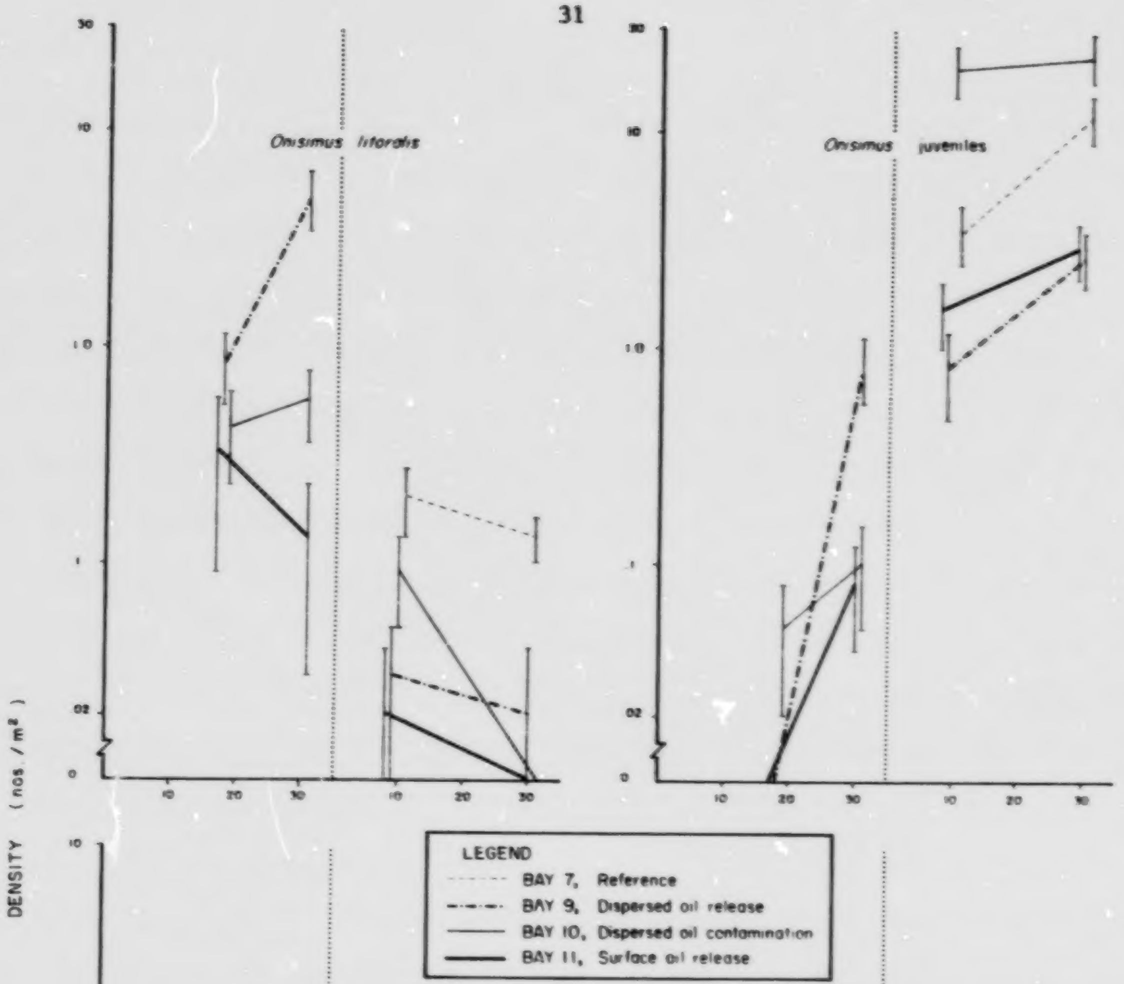

FIGURE 4. Densities of Onisimus amphipods in the under-ice habitats of four bays at Cape Hatt, Baffin Island, during May 1981 (pre-spill) and May 1982 (post-spill). Data are expressed as the mean of 10-16 replicate 4 m^2 net samples; vertical lines show standard error.

bays than others. With the exceptions noted in the previous paragraph, these differences were relatively consistent between the two sampling periods in May of each year.

Temporal effects.--Both year-to-year and seasonal variability were evident in the densities of under-ice amphipods. The predominant seasonal trend was an increase in density from early or mid May to late May (Table 3; Fig. 3 and 4). Seasonal increases in density were apparent in both years and in all bays for *Onisimus* juveniles, *Onisimus glacialis*, and all amphipods together. *Weyprechtia pinguis* and *Ischyrocerus* sp., on the other hand, showed significant seasonal increases only in 1981; no change occurred between sampling dates in May 1982 (Table 3). Densities of *Gammarus setosus* also increased during May 1981; the significant bay x date interaction (Table 3) was due to bay-to-bay differences in rates of increase. However, in 1982 densities of *Gammarus setosus* increased from early to late May in two bays, and decreased in two others. In both years, total amphipod biomass increased during May in some bays and decreased in others, and in 1981 the same was true for densities of *Onisimus litoralis*. The only case in which there was a consistent seasonal decrease in abundance in all bays was *Onisimus litoralis* in 1962; however, the significance of this is uncertain due to the low numbers of individuals present.

The observed seasonal increases in many under-ice amphipod species are likely related to the under-ice algal bloom. A distinct seasonal cycle in under-ice algae has often been observed (Horner and Alexander 1972; Clasby et al. 1973; Horner 1976, 1977). Increases in standing stocks and productivity begin sometime in April and generally peak in May or early June, at which time the dense algal layer sloughs off the bottom of the ice. Under-ice chlorophyll concentrations at Cape Hatt increased significantly during 16-30 May 1981, and there was no indication that the bloom had begun to decline at the end of May.

Year-to-year comparisons are given in Table 4. The only species considered are those whose densities were high in both years. Only the late May sampling period in each year is considered. Year-to-year variation was significant in two of four unambiguous cases (i.e. in 2 of 4 analyses where the year x bay interaction was not significant). Both density and biomass of *Weyprechtia pinguis* in late May were lower in 1982 than in 1981 (Fig. 3, Appendix C). Neither biomass of *Gammarus setosus* nor density of *Ischyrocerus* sp. varied between the two years (Table 4). In some cases where the interaction term was significant, inspection of the data indicates that the interaction was due to among-bay differences in the rate, and not the direction, of change. In these cases, and for species whose densities were too low to warrant analysis, the predominant annual trend is a decrease in numbers or biomass from 1981 to 1982. This is the case for density of *Gammarus setosus*, biomass of *Ischyrocerus* sp. and density and biomass of *Onisimus litoralis*. Only one group of amphipods shows a consistent increase from 1981 to 1982: *Onisimus juveniles*.

Annual variability in amphipod densities may also be related to changes in the abundance of ice algae, which in turn may depend on differences in snow cover. Snow cover may affect under-ice chlorophyll concentrations (Grainger 1977; Horner et al. 1974), productivity rates (Welch and Kalff 1975), and the timing of the spring bloom (Cross 1982a). In the study bays

Table 4. Annual comparisons of under-ice amphipod densities and biomasses in three bays[1] at Cape Hatt, Baffin Island, during late May 1981 and 1982[2]. F-values are shown with significance levels (ns = P>0.05; * P≤0.05; ** P≤0.01; *** P≤0.001). Significance levels are not shown for main effects when the interaction term was significant.

		Source of Variation, (df) and Group Means Ranking[3]					
		Two-factor Analysis of Variance			One-factor Analysis of Variance (years)		
Taxon	Variable	Bay (2,74 df)	Year (1,74 df)	Bay x Year (2,74 df)	Bay 9 (1,24 df)	Bay 10 (1,26 df)	Bay 11 (1,24 df)
Onisimus juveniles	Abundance	21.83	113.25	25.04 ***	5.15 * [81<82]	180.07 *** [81<82]	12.32 ** [81<82]
	Biomass	20.54	95.24	23.74 ***	2.19 ns	209.36 *** [81<82]	11.74 ** [81<82]
Gammarus setosus	Abundance	59.54	30.89	10.98 ***	0.41 ns	5.06 * [82<81]	32.60 *** [82<81]
	Biomass	139.85 *** [9<10<11]	1.46 ns	0.37 ns			
Ischyrocerus sp.	Abundance	35.01 *** [9<10,11]	1.69 ns	2.46 ns			
	Biomass	31.87	4.49	3.39 *	17.25 *** [82<81]	0.36 ns	1.93 ns
Weyprechtia pinguis	Abundance	12.97 *** [10,11<9]	22.93 *** [82<81]	0.03 ns			
	Biomass	23.47 *** [11<10<9]	5.11 * [82<81]	0.26 ns			
Amphipoda	Abundance	8.47	1.28	14.31 ***	10.61 ** [82<81]	10.57 ** [81<82]	9.05 ** [82<81]
	Biomass	4.78	3.72	9.34 ***	15.22 *** [82<81]	2.31 ns	0.28 ns

[1] Bays 9 (dispersed oil release), 10 (dispersed oil contamination) and 11 (surface oil release).

[2] 31 May 1981 (Pre-spill) and 30-31 May 1982 (Post-spill); oil was released in late August 1981.

[3] Duncan's Multiple Range Test, $\alpha = .05$.

at Cape Hatt, snow cover did vary between 1981 and 1982, but the variation was not consistent among bays (see 'Site Description'). Thus the year-to-year variability in amphipod abundance cannot be attributed to this factor alone. Nonetheless, snow cover must be taken into account in any interpretation of interactions between bays and years.

Intertidal Habitat

The amphipods *Gammarus setosus* and *Onisimus litoralis* are the only two amphipod species previously reported to be abundant in arctic intertidal habitats (Sekerak et al. 1976; Thomson et al. 1978; Thomson et al. 1979; Thomson and Cross 1980; Cross 1982b). Substrates in the intertidal habitats where sampling has been carried out are generally composed of rocks and pebbles with small amounts of sand, although occasionally sand beaches have been included (Thomson et al. 1979; Thomson and Cross 1980). *Gammarus setosus* and *Onisimus litoralis* are both most abundant at low tide; the former shows an apparent preference for rocks >5 cm in diameter, whereas *Onisimus litoralis* occurs primarily in substrates of sand and small pebbles (Thomson et al. 1979).

Thus, factors affecting the abundance of intertidal amphipods include substrate type and tide. In each of the bays at Cape Hatt, rock and cobble were the predominant substrates in the upper and mid intertidal areas, whereas finer sediments (mostly sand) became more common in the low intertidal areas. Substrate type and tide may, therefore, be expected to affect abundance of intertidal amphipods within the study bays.

Intertidal sampling at Cape Hatt was carried out at low tide in each year. The range of tide levels sampled was greater in 1981 (26 to 103 cm below mean tide) than in 1982 (66 to 101 cm below mean) because of sampling date. This factor must be taken into account in the interpretation of spatial and temporal distributions.

Spatial Effects.--During 1981, two amphipod species were dominant in the intertidal habitat at Cape Hatt: Gammarus setosus and Onisimus litoralis. The latter species was found only in Bays 10 and 11, and was relatively abundant only in Bay 11 and only in August (Fig. 5; Appendices D and E). August to September changes in the abundance and biomass of Gammarus setosus were not consistent among bays. This interaction (Table 5) necessitated the use of separate one-factor analyses (bay effects) for each month. Numbers and biomass of Gammarus setosus differed among bays only in September (Cross 1982b). At this time, density of Gammarus setosus was highest in Bay 10 and lowest in Bays 9 and 11; biomass was also highest in Bay 10, but in this case values were lower in Bay 9 than in Bay 11 (Fig. 6).

During 1982, differences among bays were significant for each of the four dominant intertidal amphipod species and also for total amphipods (Table 5). Numbers and biomasses of Gammarus setosus were lowest in Bay 11 and higher and similar in the other three bays (Fig. 6, Table 5). Numbers and biomasses of both species of Onisimus were highest in Bay 11 and lowest in Bay 7 (Table 5); in each species the greatest difference was between Bay 7 and the other three bays, and differences among Bays 9, 10 and 11 were apparently greater in August than in September (Fig. 5). Monoculodes packardi was less abundant in Bays 7 and 11 than in Bays 9 and 10, in terms

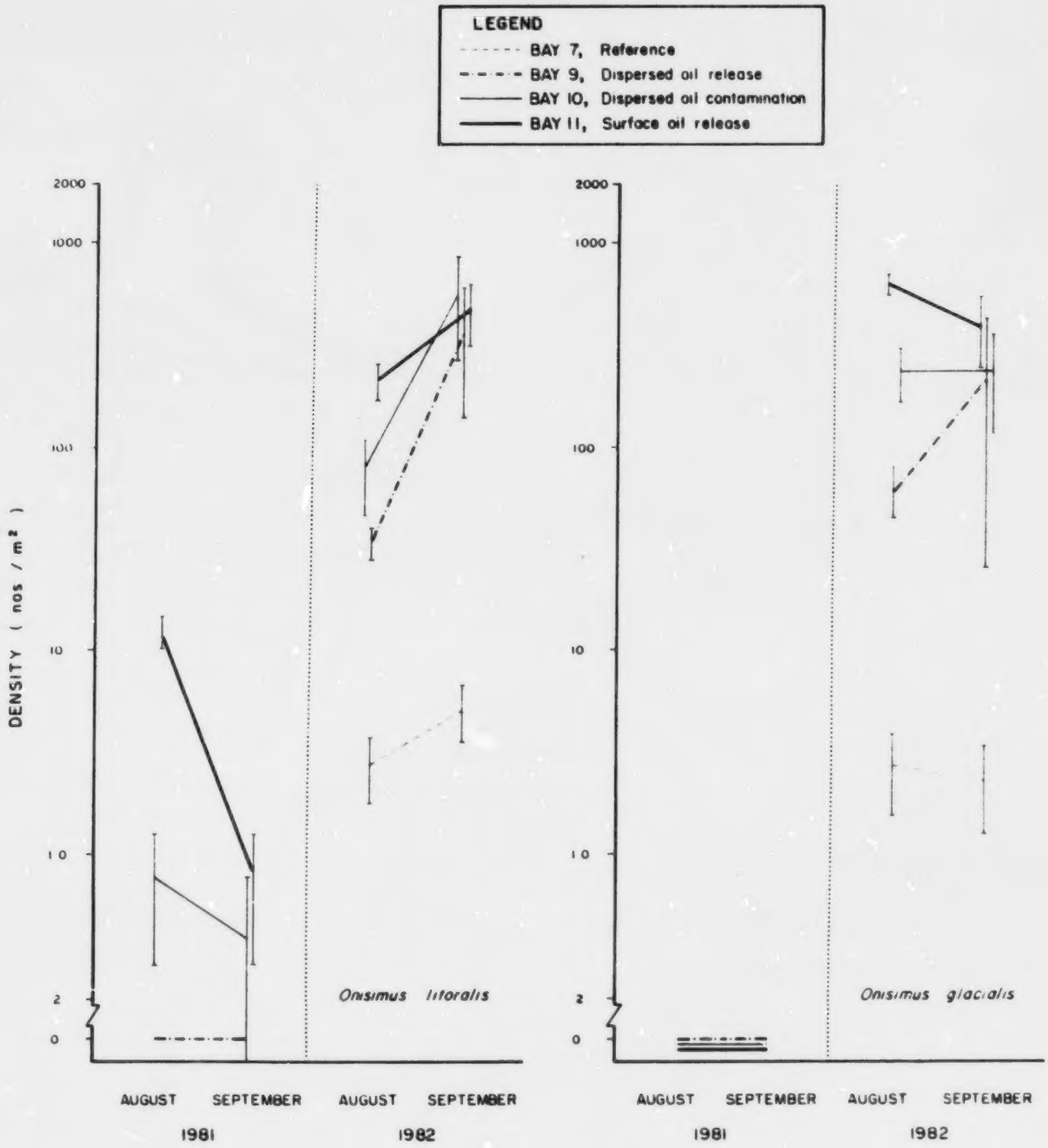

FIGURE 5. Densities of Onisimus litoralis and Onisimus glacialis in the intertidal habitats of four bays at Cape Hatt, Baffin Island, during August and September 1981 and 1982. Oil was released in late August 1981. Data are expressed as the mean of 10 samples, each covering 0.25 m^2; vertical lines show standard error.

Table 5. Comparison of densities and biomasses of amphipods in intertidal habitats in three or four bays[1] at Cape Hatt, Baffin Island, during August and September 1981 and 1982[2]. F-values are shown with significance levels (ns = $P>0.05$; * $P\le 0.05$; ** $P\le 0.01$; *** $P\le 0.001$). Significance levels are not shown for main effects when the interaction term was significant.

Year	Taxon/df	Variable	Source of Variation			Group Means Ranking[3]	
			Bay	Month	Bay x Month	Bays	Months
1981	*Gammarus setosus*	Abundance	1.34	6.90	9.92 ***		
		Biomass	0.20	3.22	6.34 **		
1982	*Gammarus setosus*	Abundance	9.59 ***	0.00 ns	0.41 ns	11<7,9,10	
		Biomass	12.99 ***	0.14 ns	0.40 ns	11<7,9,10	
	Onisimus litoralis	Abundance	43.99 ***	19.14 ***	2.22 ns	7<9,10<11	Aug<Sept
		Biomass	52.31 ***	21.94 ***	1.04 ns	7<9,10<11	Aug<Sept
	Onisimus glacialis	Abundance	44.98 ***	5.97 *	0.75 ns	7<9<10<11	Sept<Aug
		Biomass	42.68 ***	3.85 ns	0.47 ns	7<9<10<11	
	Monoculodes packardi	Abundance	12.18 ***	1.13 ns	1.41 ns	7,11<9,10	
		Biomass	11.67 ***	2.98 ns	1.88 ns	7,11<9,10	
	Amphipoda	Abundance	7.51 ***	1.19 ns	0.30 ns	7<9,10,11	
		Biomass	3.65 *	3.62 ns	0.45 ns	7,10,11<9	
1981	Degrees of freedom		2,54	1,54	2,54		
1982	Degrees of freedom		3,72	1,72	3,72		

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[1] Bays 9 (dispersed oil release), 10 (dispersed oil contamination) and 11 (surface oil release) in 1981; Bays 7 (reference), 9, 10 and 11 in 1982.

[2] Oil was released in late August 1981.

[3] Duncan's Multiple Range Test, $\alpha = .05$.

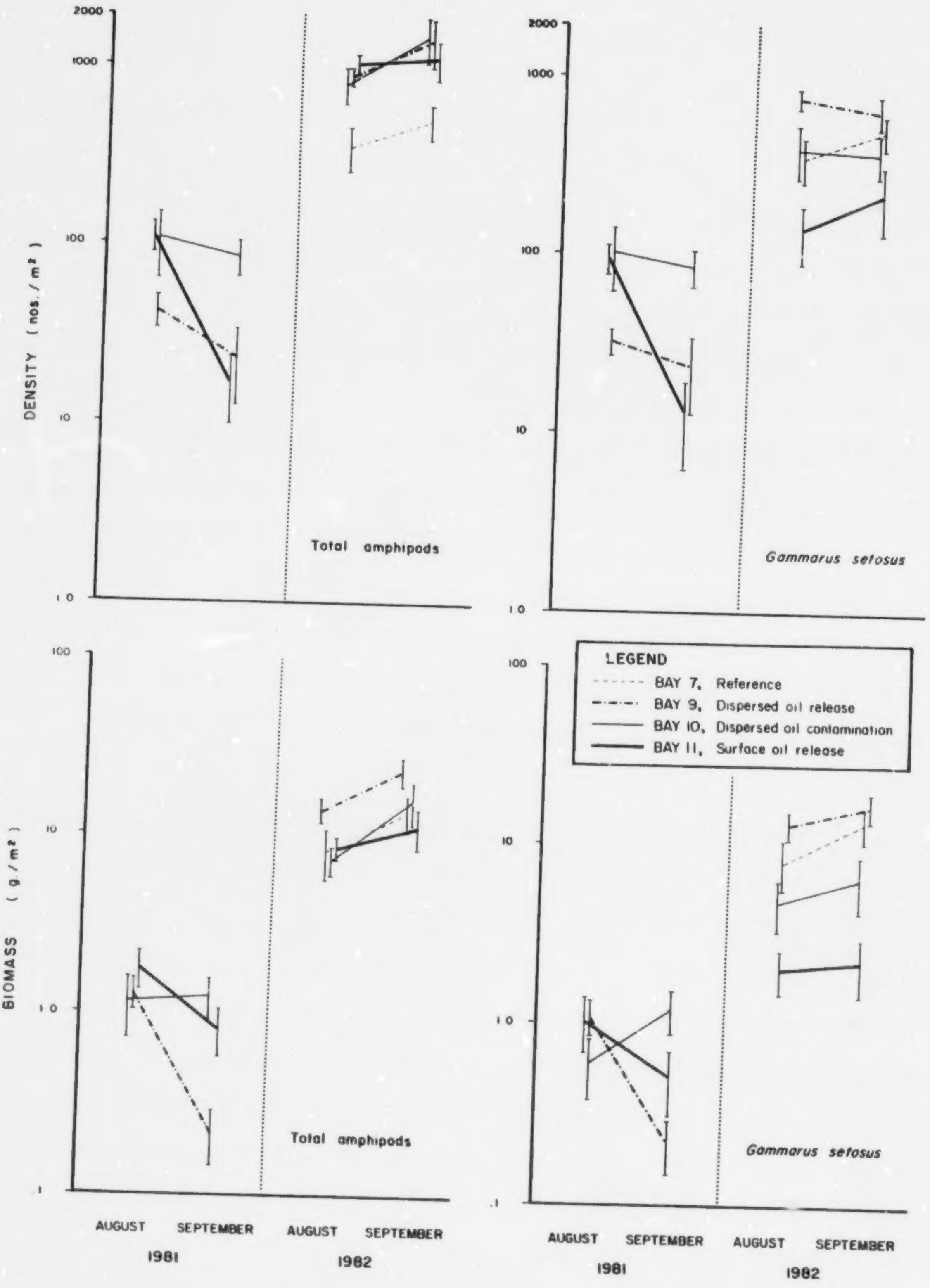

FIGURE 6. Densities and biomasses of Gammarus setosus and total amphipods in the intertidal habitats of four bays at Cape Hatt, Baffin Island during August and September 1981 and 1982. Oil was released in late August 1981. Data are expressed as the mean of 10 samples, each covering 0.25 m^2; vertical lines show standard error.

of both abundance and biomass. Total amphipod abundance and biomass were similar in 3 of 4 bays. Bay 7 supported the lowest total density and Bay 9 supported the highest total biomass of intertidal amphipods (Fig. 6).

In neither year do the observed among-bay differences in amphipod distribution appear to be related to tide level. In 1981, tide levels at which sampling took place were more similar among bays in September than in August (Appendix D), whereas abundance and biomass of *Gammarus setosus* were more variable in September. In August, tide levels were higher in Bay 11 than in Bay 10, and *Onisimus litoralis* was more abundant in Bay 11; this is not consistent with the observed relationships between substrate type, tide level and density of this species (see above). During 1982, among-bay differences were considerable in all amphipod species examined, whereas tide levels at which sampling took place were relatively constant among bays (Appendix D).

Temporal Effects.--During 1981, differences in abundance and biomass of the dominant intertidal amphipods were not consistent among bays (Fig. 5 and 6). In 1982, differences between August and September were significant only for density and biomass of *Onisimus litoralis* ($P \leq 0.001$) and for density of *Onisimus glacialis* ($P \leq 0.05$). *Onisimus litoralis* increased in abundance between August and September, whereas densities of *Onisimus glacialis* were generally lower in September (Table 5); the apparent August to September increase in Bay 9 (Fig. 5) was the result of one sample containing very large numbers of individuals.

In contrast to the apparent lack of seasonal effects, year-to-year differences in the abundance and biomass of intertidal amphipods were considerable. This is immediately apparent upon inspection of the data (Fig. 5 and 6; Appendices D and E); differences were so large that analyses were not carried out. Depending on bay and month, mean densities of total amphipods in 1982 were 8-68 times greater, and mean biomasses were 5-107 times greater than in 1981. Moreover, increases between years included all four of the dominant species collected in the intertidal habitat in 1982. Gammarus setosus and Onisimus litoralis increased in similar proportions to those given above for total amphipods. Onisimus glacialis and Monoculodes packardi were absent in 1981, whereas in 1982 densities of these two species were as high as 633.6 and 287.6 individuals/m^2, respectively (Appendix D).

This difference may represent a real change in amphipod distributions from one year to the other. Higher 1982 densities of Onisimus glacialis, for example, are likely related to the observed increases in densities of Onisimus juveniles under the ice in May (Fig. 4). In turn, this indicates that 1981 was a year of successful breeding, at least in some locations (see below). Year-to-year differences may also be related to year-to-year differences in tide levels in combination with substrate differences within bays, or to some other type of sampling bias. Sampling was at lower tide levels in 1982 than in 1981 (66-101 vs. 26-64 cm below mean) in all but one bay/month combination (Appendix D). In this one case differences between years were smaller, but still considerable. Hence it is likely that another factor is involved. In any case, these differences confound the interpretation of oil effects and must be taken into consideration.

Oil Effects

Significant interaction terms in analyses of variance have indicated oil effects on dominant amphipods in both under-ice and intertidal habitats (Tables 4 and 5). These analyses were based on data collected in three bays (one surface oil release bay and two dispersed oil release bays) during pre- and post-spill periods (late May 1981 and 1982; August and September 1981); oil releases took place in late August 1981. Interpretation of these apparent oil effects is supplemented with data collected in a fourth (reference) bay and in August and September 1982 (one year post-spill).

Dominant amphipod taxa in under-ice and intertidal habitats in the study area for which oil effects have been indicated are *Gammarus setosus*, *Ischyrocerus* sp., and *Onisimus* juveniles. The effects of the surface and dispersed oil releases on each of these species will be discussed.

Gammarus setosus

Lagomedio crude oil was released in Bay 11 between the August and September sampling periods in 1981, and a relatively even coating of oil was deposited on the beach (intertidal area) of Bay 11 by the falling tide. Observations following the oil release (Cross and Thomson 1982), inspection of the data (Fig. 6) and significance of the bay x time interaction terms in Table 5 all indicate that oil affected the amphipods that occupied the intertidal habitat. The numbers of intertidal *Gammarus setosus* decreased somewhat in Bays 9 and 10 (dispersed oil bays) from August to September 1981, but the corresponding decrease in Bay 11 was much more marked (September densities were 56.2, 83.2 and 13.4% of August values in Bays 9, 10 and 11, respectively). Biomass of *Gammarus setosus*, on the other hand, decreased more in Bay 9 than in Bay 11, and increased in Bay 10 (Fig. 6). Bay 9 was the study bay that received the highest concentrations of dispersed oil (an order of magnitude higher than those in Bay 10). Thus there appear to have been effects on *Gammarus setosus* related both to the untreated oil and dispersed oil releases.

Differences in the results for density and biomass data suggest that these were size-specific effects, and other data confirm this. Inspection of length-frequency data (Fig. 7) shows that the surface oil affected small *Gammarus setosus* (0+ year class) to a much greater extent than older individuals. Length-frequency data are not shown for the intertidal habitat in Bay 9, but in that case the converse was true: numbers of small (0+) individuals collected in pre- and post-spill periods (August and September) were similar (42 and 46, respectively), whereas the number of larger individuals collected was much lower in September (13) than in August (65). No size effect was apparent in Bay 10 (Fig. 7).

The persistence of one or both of the observed oil effects (untreated oil, dispersed oil) until May 1982 was indicated by a significant period x year interaction in the analyses of pre- and post-spill densities of *Gammarus setosus* under the ice in May (Table 4). However, one-factor analyses show bay differences in pre- to post-spill change that are not consistent with those observed in the previous summer or with the type or level of oil contamination. Densities of *Gammarus setosus* on the under-ice surface decreased from 1981 to 1982 in Bay 11, but also decreased in Bay 10 where no

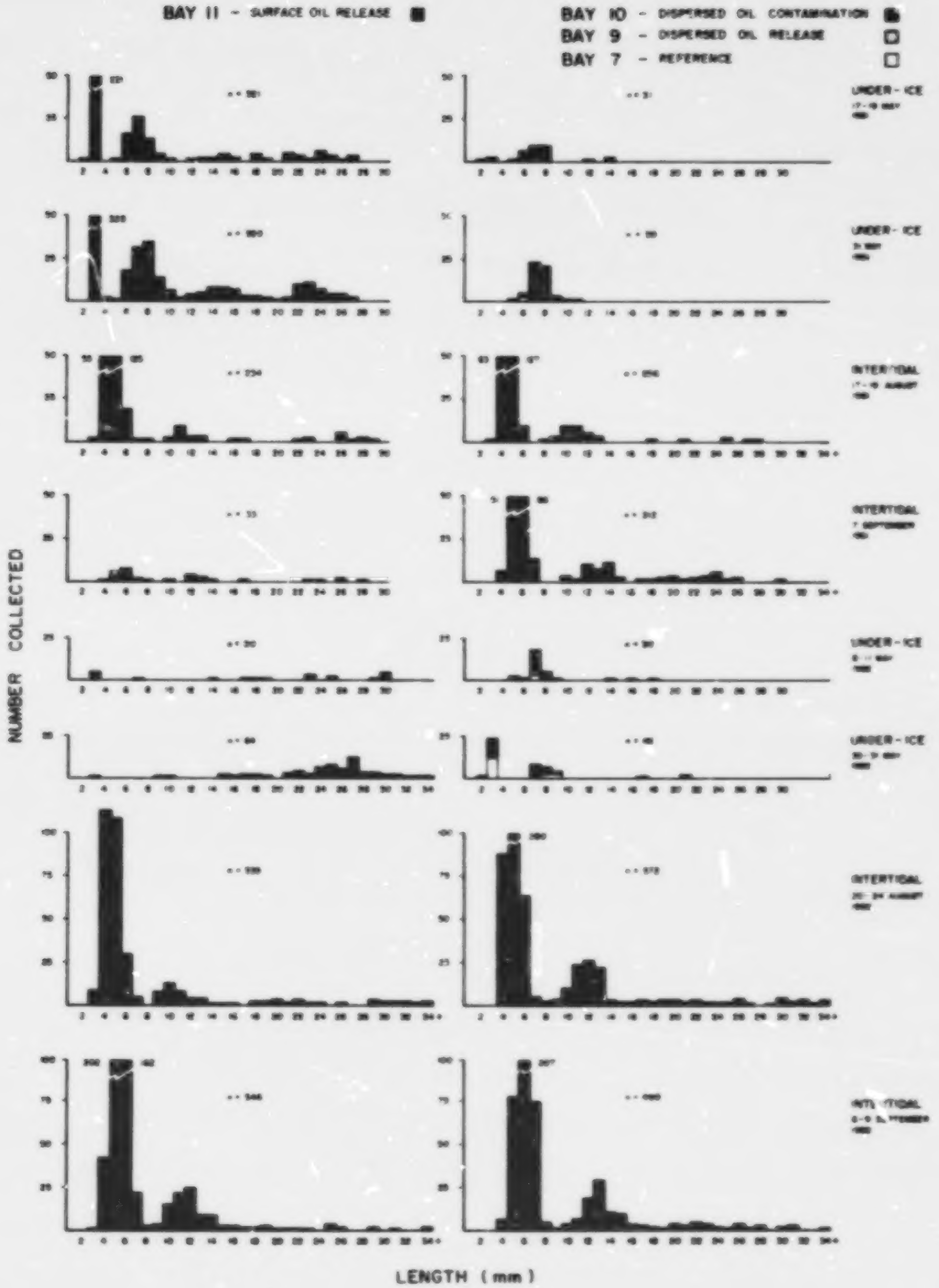

FIGURE 7. Length-frequency histograms for Gammarus setosus in the under-ice and intertidal habitats of four bays at Cape Hatt, Baffin Island, during May, August and September 1981 and 1982. Oil was released in late August 1981.

effect was apparent in the summer of 1981. There was no significant difference between the 1981 and 1982 densities of Gammarus setosus under the ice in Bay 9; densities were low in both years.

Inspection of size-frequency distributions, on the other hand, indicates that effects of the surface oil release in late August 1981 persisted until May 1982. In Bay 11, numbers of newly released juveniles (3 mm in length) and one-year-olds (6-10 mm) on the under-ice surface were much lower in May 1982 than in May 1981 (Fig. 7). In the other three bays, both size classes were present (albeit in low numbers) in May 1982. Females brooding young were common in Bay 11 during late May of each year; the release of these young in Bay 11, however, appeared to be delayed in 1982. Differences from 1981 to 1982 in both cohorts can be attributed to the surface oil release in August 1981.

Both of these year classes were present in the intertidal habitat of Bay 11 during August and September 1982 (Fig. 7). Hence the population appears to have at least partially recovered one year following the release of untreated oil. The delayed release of juveniles in the surface release bay in May 1982, however, may have resulted in reduced size of individuals in this year class. The median size of the 0+ year class in Bay 11 was 4 mm in August 1982 as compared with 5 mm in August 1981 (Fig. 7); the latter appears to be the norm in the other bays in both years (Fig. 7 and 8). The implications of this reduced size on survival or fitness are not known.

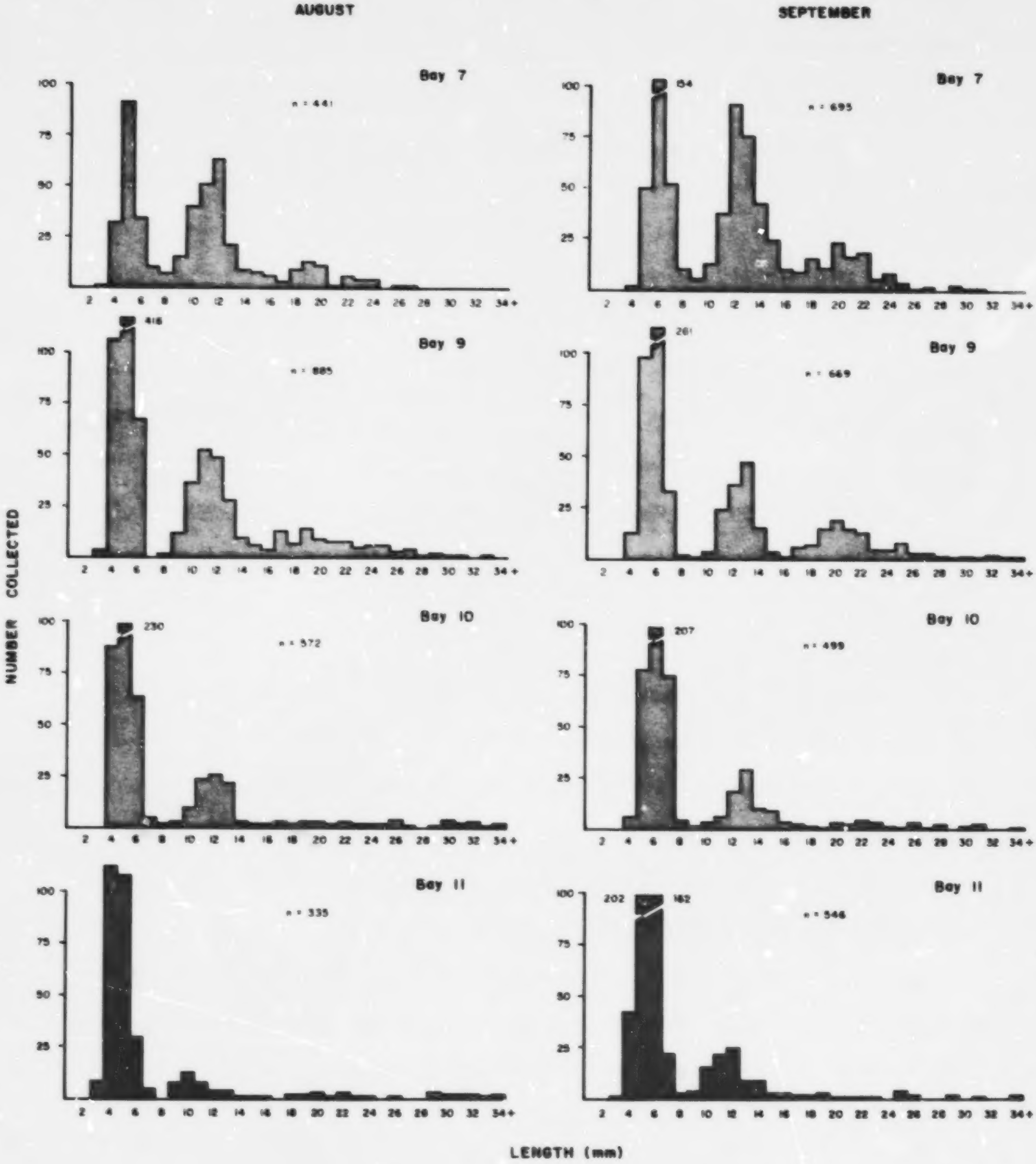

FIGURE 8. Length-frequency histograms for *Gammarus setosus* in the intertidal habitats of four bays at Cape Hatt, Baffin Island, during August and September 1982.

Among-bay differences in the densities of intertidal Gammarus setosus in 1982 further indicate incomplete recovery from the effects of the surface oil release in 1981. During August and September 1982, densities and biomasses were lower in Bay 11 than in the other three bays (Table 5; Fig. 6). In August 1981, on the other hand, densities were highest in Bays 10 and 11, and biomasses were similar in all three bays. Effects of the dispersed oil release were not apparent one year following the release. Density and biomass of intertidal Gammarus setosus in 1982 were highest in Bay 9 (Fig. 6), and the population structure in this bay appeared to be normal (Fig. 8).

In summary, there was an unequivocal effect of the surface oil release on Gammarus setosus. Direct oiling of intertidal populations in Bay 11 caused immediate mortality. Densities in this bay were significantly reduced three weeks after the oil release, particularly in the 0+ year class. This cohort was almost absent from the under-ice surface in the following spring but was well represented in the intertidal habitat one year following the oil release. These individuals must have been recruited from adjacent areas. Larvigerous females were present on the under-ice surface in Bay 11 in May of both the pre- and the post-spill years, but the release of juveniles was delayed in 1982. This delay apparently resulted in reduced size of the 1982 0+ year class in the intertidal habitat in August and September.

The dispersed oil release, on the other hand, seems to have affected older Gammarus setosus (1 and 2+ year classes). Densities of these individuals were markedly reduced approximately one week following the release, but it is uncertain whether mortality or emigration was the cause of this decrease. Densities on the under-ice surface were low in both the pre-

and the post-spill years. No effects were apparent in abundance and population structure data collected in the intertidal habitat one year following the release.

Onisimus juveniles

Numbers of *Onisimus* juveniles on the under-ice surface increased greatly from May 1981 to May 1982 in all three bays that were sampled in both years. Oil effects on *Onisimus* juveniles were indicated by significant bay x year interaction terms (Table 4). Increases in density and biomass of juvenile *Onisimus* from 1981 to 1982 were much more pronounced in Bay 10 than in Bays 9 or 11 (Fig. 4; Appendix C). These differences, together with the observed high densities of these juveniles in Bay 7 (reference bay) during May 1982, suggest that a natural population increase from 1981 to 1982 may have been partly inhibited in bays that received high levels of dispersed oil (Bay 9) or surface oil (Bay 11).

Ischyrocerus sp.

Ischyrocerus sp. was sufficiently abundant to warrant analysis only in the under-ice habitat. Biomass of this species on the under-ice surface decreased significantly from late May 1981 to late May 1982 in Bay 9 but not in Bays 10 or 11 (Table 4). This suggests that biomass was reduced by the dispersed oil released in Bay 9 between the two sampling dates. When density data were considered, the interaction term was not significant, nor was there any significant difference in densities between the late May sampling periods of the two years. Differences in the results for density and biomass suggest that there were size-specific effects. Numbers of Ischyrocerus sp. in Bay 9 were too few, however, to warrant any analysis of size effects (only 25 individuals collected in May 1982).

Ischyrocerus sp. was sparsely distributed (0.7 individuals/m^2) in the sublittoral habitat of Bay 9 at the time of the dispersed oil release (Cross 1982b). The occurrence of Ischyrocerus anguipes on the under-ice surface in offshore locations (Cross 1980, 1982a), together with its overall low abundance in the sublittoral habitat at Cape Hatt in 1981 (Cross 1982b), suggest that under-ice populations of this species may be recruited, at least in part, from the water column. In this case the size effect suggested above probably was not related to the release of dispersed oil at Cape Hatt. Stephensen (1935), on the other hand, reported an association between Ischyrocerus anguipes and shallow water macroalgae. In each of five sampling periods in 1980-1982, Bays 10 and 11 supported higher biomasses of macroalgae at 3 m depth than did Bays 7 or 9 (Cross et al. 1983). In May 1981 and 1982, Ischyrocerus sp. was also more abundant in Bays 10 and 11 than in Bays 7 and 9 (Fig. 9). Population structures of Ischyrocerus sp. on the under-ice surface differed between Bays 10 and 11, and mean size was smaller in Bay 11 during all four spring sampling periods (Fig. 9). These observations indicate that under-ice populations of this species at Cape Hatt are of benthic rather than pelagic origin, and furthermore, that these populations are relatively immobile on a large (bay) scale.

Therefore, we must conclude that there was an effect of dispersed oil on Ischyrocerus sp., and that this effect may have been size-specific. Additional spring sampling in subsequent years would be required to determine if populations of this species in the dispersed oil bay will recover.

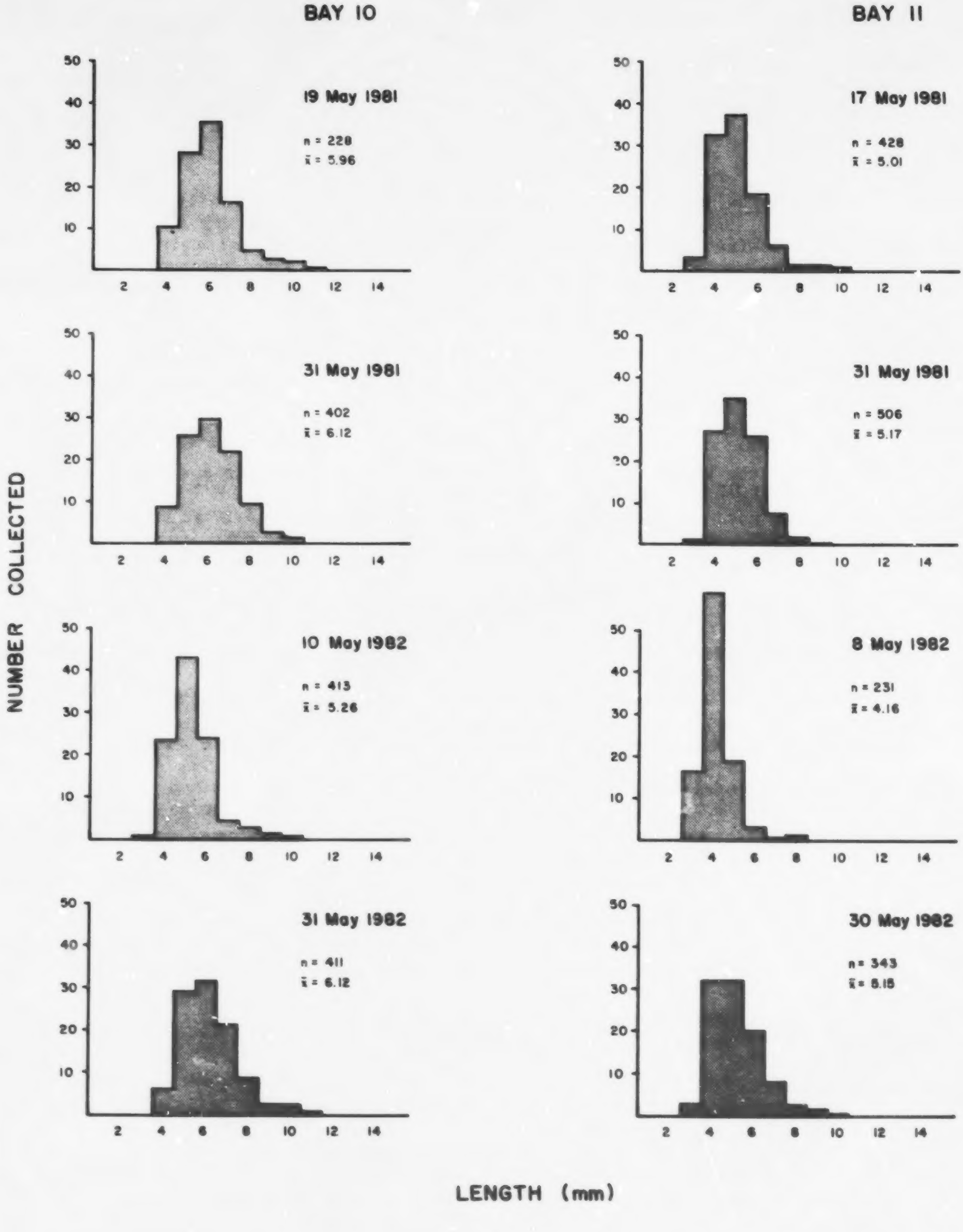

FIGURE 9. Length-frequency histograms for Ischyrocerus sp. in the under-ice habitats of two bays at Cape Hatt, Baffin Island, during May 1981 (pre-spill) and May 1982 (post-spill).

Productivity and Biomass of Under-Ice Algae

Site Description

The under-ice surface in the study areas was smooth and relatively flat, with shallow hummocks and ridges. Ice depth was 135 cm at the entry hole. Snow depths over the study areas (locations) on 3 June 1982 were 9.8 ± 1.7 cm ($n = 14$) and 18.2 ± 7.4 cm ($n = 30$) in Locations 1 and 2, respectively. The site was selected within Bay 13 on 7 May, with low even snow depth (~10 cm) and 10 m water depth as the criteria. Differences in snow cover between locations were the result of high winds, snow fall and drifting snow on 12 and 13 May; snow cover was higher and more variable over Location 2, which was in the lee of two tents during the period of high winds. The amount of light penetrating the snow and ice varied both spatially (primarily because of variable snow cover) and temporally; temporal variation, within and among days, resulted from changes in cloud conditions and in solar elevation. Total *in situ* radiation varied among enclosures and periods by almost an order of magnitude.

Salinity of ice (+ water) samples ranged from 30.1-32.4 ‰; no consistent differences were apparent among days on which determinations were made (18 May-1 June). Snow melt was beginning near the end of May, but no obvious effects were observed under the ice.

Ambient (pre-incubation) nutrient samples were collected in duplicate on 18, 19, 27 and 28 May and 1 June. Phosphate concentrations were from 1.25 to 1.90 µmol/L, nitrate concentrations were from 3.04 to 10.23 µmol/L, and ammonia concentrations were from 0.65 to 2.47 μmol/L. These nutrient concentrations fall within ranges previously reported (e.g., Alexander et al. 1974; Cross 1980, 1982a; Grainger and Hsiao 1982), and are sufficient to support the growth of ice microalgae (Hsiao 1980).

Phytoplankton Biomass and Productivity

Biomass (as estimated by chlorophyll a concentration), and productivity were very low in the water immediately beneath the ice at Cape Hatt in 1981 and 1982. Concentration of chlorophyll a in control water samples were 1.19 ± SD 0.47 mg/mg^3 (n = 8) and 1.93 ± 3.14 mg/m^3 (n = 24) in 1981 and 1982, respectively. The concentration of algal cells in near-ice water was 1.3 ± 0.7 x 10^4 cells/L (n = 17) during 18 May to 2 June 1982, and dominance was shared by pennate diatoms (48%) and microflagellates (45%). Biomass and standing stocks at Cape Hatt were similar to those reported in other locations (Alexander et al. 1974; Cross 1980, 1982a; Grainger and Hsiao 1982). After correction for dilution (sampled ice depth = 1 to 2 cm; chamber depth = 15 cm), algal concentrations per unit volume were lower in the water than in the ice by 2 to 3 orders of magnitude.

Productivity in the near-ice water was also low during 1981 and 1982; indeed, after dark ^{14}C uptake was subtracted from light ^{14}C fixation, productivity values for most samples were slightly negative. Mean uptake rates of radiocarbon in dark chambers were 0.28 ± 0.09 $mgC/m^3.h$ (n = 4) and 0.29 ± 0.26 $mgC/m^3.h$ (n = 11) in 1981 and 1982, respectively. Net productivity rates, calculated by subtracting dark values from values measured in light chambers, were -0.033 ± 0.23 (n = 4) and -0.0002 ± 0.2885 $mgC/m^3.h$ (n = 13) in the two years of study. There was no significant difference (P>0.5) between light and dark radiocarbon uptake in 1982 (paired t-test on scintillation counts for nine pairs of chambers; t = 0.20, P>0.5). Alexander et al. (1974) also reported low productivity estimates for phytoplankton in May at Barrow, Alaska: averages of 0.30 and 0.23 mg C/m^3 for 1972 and 1973, respectively.

Ice Algal Composition and Distribution

Major groups of microalgae were enumerated in a total of 174 ice samples collected in 1982 (including 83 controls), and species were identified and counted in 72 of these samples (32 controls). In contrast with samples of near-ice water, samples containing the bottom 1-2 cm layer of ice were overwhelmingly dominated by pennate diatoms (89% of algal cells in 83 control samples). A total of 59 species or varieties of microalgae were identified, and at least another 17 distinct but unidentified species were found in 72 samples. Sixty-one of the 76 species were pennate diatoms (Table 6).

Nitzschia grunowii was the dominant species in 68 of 72 samples; it comprised an average of 54.8% of total algal numbers in 32 control samples. Nitzschia frigida was dominant in 3 samples and ranked second in most of the remainder of the 72 samples. It comprised an average of 15.2% of total cells in 32 control samples. A similar dominance of these two species in Pond Inlet was reported by Cross (1982a).

Microalgae were relatively evenly distributed on a small scale (i.e. within the 1.2 m^2 enclosures); the standard deviation was usually much less than the mean (Table 7). Spatial variation on a larger scale (among

Table 6. Genera and species of microalgae found in diver-collected ice cores[1] from Cape Hatt, Baffin Island, during 18 May-2 June 1982[2].

- Bacillariophyceae
  - Centrales[3]
    - *Chaetoceros*[3]
      - *C. compressus* Lauder
      - *C. karianus* Grunow in Cleve *et* Grunow
      - *C. septentrionalis* Östrup
      - *C. simplex* Ostenfeld
  - Coscinodiscus[3]
    - *Melosira*[3]
      - *M. arctica* (Ehrenberg) Dickie in Pritchard
    - *Thalassiosira*[3]
      - *T. nordenskioldii* Cleve
  - Pennales[3]
    - *Achnanthes*
      - *A. taeniata* Grunow
    - *Amphiprora*[3]
      - *A. concilians* Cleve
      - *A. gigantea* var. *septentrionalis* (Grunow in Cleve *et* Grunow) Cleve
      - *A. kjellmanii* Cleve
      - *A. palludosa* Wm. Smith
    - *Amphora*[3]
      - *A. laevis* var. *laevissima* (Gregory) Cleve
      - *A. proteus* Gregory
    - *Cylindrotheca*
      - *C. closterium* (Ehrenberg) Reimann *et* Lewin
    - *Diploneis*
      - *D. litoralis* Cleve
      - *D. litoralis* var. *arctica* Cleve
      - *D. litoralis* var. *clathrata* (Östrup) Cleve
    - *Gomphonema*[3]
      - *G. exiguum* Kutzing
    - *Licmophora*[3]
    - *Navicula*[3]
      - *N. algida* Grunow
      - *N. cancellata* Donkin
      - *N. crassirostris* Grunow in Cleve *et* Grunow
      - *N. digitoradiata* (Gregory) Ralfs
      - *N. directa* (Wm. Smith) Ralfs
      - *N. gastrum* (Ehrenberg) Kutzing
      - *N. gelida* Grunow
      - *N. membranacea* Cleve
      - *N. novadicipiens* Hustedt
      - *N. pelagica* Cleve
      - *K. ryncocephala* Kutzing
      - *N. salinarum* Grunow
      - *N. spicula* (Hickie) Cleve
      - *N. transitans* Cleve
      - *N. transitans* var. *incudiformis* (Grunow in Cleve) Cleve
      - *N. trigonocephala* Cleve
      - *N. valida* Cleve and Grunow
      - *N. valida* var. *minuta* Cleve
    - *Nitzschia*[3]
      - *N. angularis* Wm. Smith
      - *N. brebissonii* var. *borealis* Grunow in Cleve *et* Möller
      - *N. cylindrus* Hasle
      - *N. delicatissima* Cleve
      - *N. dissipata* (Kützing) Grunow
      - *N. distans* Gregory
      - *N. frigida* Grunow
      - *N. grunowii* Hasle
      - *N. hybrida* Grunow in Cleve *et* Grunow
      - *N. laevissima* Grunow in Cleve *et* Möller
      - *N. lecointei* Van Heurck
      - *N. linearis* (Agardh) Wm. Smith
      - *N. longissima* (Brebisson in Kützing) Grunow
      - *N. seriata* Cleve
      - *N. sigma* (Kützing) Wm. Smith
    - *Pinnularia*[3]
      - *P. ambiqua* Cleve
      - *P. quadratarea* (Schmidt) Cleve
      - *P. quadratarea* var. *bicontracta* (Östrup) Heiden in Schmidt et al.
      - *P. quadratarea* var. *constricta* (Östrup) Heiden in Schmidt et al.
    - *Pleurosigma*[3]
      - *P. angulatum* (Quekett) Wm. Smith
      - *P. elongatum* Wm. Smith
    - *Stenoneis*
      - *S. inconspicua* var. *baculus* (Cleve in Cleve *et* Möller) Cleve
- Chlorophyceae
  - *Carteria*[3]
- Chrysophyceae
  - *Dinobryon*
    - *D. balticum* (Schuett) Lemmermann
- Dinophyceae[3]
  - *Gymnodinium*[3]
  - *Peridinium*[3]
  - *Prorocentrum*[3]
- Euglenophyceae[3]
  - *Euglena*[3]
- Craspedophyceae[3]

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[1] 72 cores 10 cm in diameter and 2-3 cm in depth.

[2] Includes both pre- and post-spill sampling periods.

[3] Taxa for which unidentified cells or colonies were found.

enclosures separated by ~ 1 to 20 m) and temporal variation (among 5 sampling periods within the period 18 May to 2 June 1982) were considerable: Total microalgal densities in control samples ranged from 1.7 to 384.7 x 10^7 cells/m^2 (Table 7). In general, cell densities increased throughout the study period. Mean cell densities (all enclosures considered) increased progressively from 90.9 ± 65.7 x 10^7 cells/m^2 (n = 43) on 18-19 May to 210.8 ± 86.2 x 10^7 cells/m^2 (n = 42) on 1-2 June. A similar trend was evident in control data (i.e. all enclosures in two pre-spill periods; control enclosures only in three post-spill periods), except that mean density was highest (375.0 ± 50.0; n = 4) on 28-29 May.

Mean ice algal densities in most locations at Cape Hatt in spring 1982 were typical of those reported for other arctic and subarctic locations. The maximum (single sample) density found at Cape Hatt (466.7 x 10^7 cells/m^2) is similar to single sample maxima in Frobisher Bay (399.3 x 10^7 cells/m^2; Grainger and Hsiao 1982) and Pond Inlet (441.4 x 10^7 cells/m^2; Cross 1982a). A higher maximum level (3420 x 10^7 cells/m^2) was reported by Hsiao (1980); however, this value was integrated for the entire ice column. Cell densities in some locations at Cape Hatt (those $<<10^9$ cells/m^2) are low relative to typical densities in spring.

Evaluation of Filtration Techniques

In the present study we used labelled inorganic carbon and a differential filtration technique (see Derenbach and Williams 1974) to estimate, during 2-3 h incubations, (1) carbon fixation by ice microalgae, (2) release of dissolved organic carbon (DOC) by algae, and (3) subsequent

Table 7. Under-ice productivity, chlorophyll a, microalgal density and *in situ* light data measured in all sampling periods at Cape Hatt, Baffin Island, during 18 May-2 June 1982[1]. Data are expressed as mean ± SD; sample sizes are given in Appendix A.

Variable	Period[1]	Location	Treatment Control	Oil[2]	Solidified Oil[2]	BP CID +Oil[2]	BP 1100WD +Oil[2]	Corexit 9527 +Oil[2]
Productivity[3] ($mgC/m^2/h$)	Pre-spill 1	1	1.50 ± 0.18	0.05	0.21 ± 0.05	2.14 ± 0.60	1.08 ± 0.19	0.30 ± 0.04
		2	1.50 ± 0.86	0.82 ± 0.23	0.33 ± 0.09	0.16 ± 0.10	0.11 ± 0.07	1.09 ± 0.34
	Pre-spill 2	1	1.92 ± 0.54	-0.08 ± 0.05	0.16 ± 0.20	1.82 ± 0.26	1.47 ± 0.24	0.49 ± 0.08
		2	2.95 ± 1.61	0.95 ± 0.52	0.70 ± 0.29	0.88 ± 0.25	-0.05 ± 0.03	1.38 ± 0.31
	Post-spill 1	1	1.78 ± 0.77	0.19 ± 0.03	1.29 ± 0.53	1.16 ± 0.44	1.20 ± 0.29	1.11 ± 0.49
		2	2.11 ± 0.53	1.90 ± 0.38	1.52 ± 0.46	1.28 ± 0.39	0.09 ± 0.07	0.94 ± 0.37
	Post-spill 2	1	2.58 ± 0.50	0.30 ± 0.03	1.46 ± 0.48	2.10 ± 0.11	1.57 ± 0.36	2.21 ± 0.15
		2	2.33 ± 0.07	2.18 ± 0.48	1.64 ± 0.55	1.53 ± 0.45	-0.00 ± 0.04	1.98 ± 0.38
	Post-spill 3	1	2.09 ± 0.00	0.38 ± 0.06	1.55 ± 0.48	1.85 ± 0.38	1.38 ± 0.25	1.39 ± 0.16
		2	2.16 ± 0.51	1.79 ± 0.03	1.12 ± 0.24	1.31 ± 0.29	0.07 ± 0.03	2.11 ± 0.42
Chlorophyll a[3] (mg/m^2)	Pre-spill 1	1	10.83 ± 1.65	3.35 ± 0.58	6.04 ± 0.70	11.66 ± 2.74	10.15 ± 1.34	7.65 ± 2.57
		2	12.80 ± 2.41	11.31 ± 0.86	10.85 ± 4.61	6.82 ± 4.14	5.78 ± 0.43	11.66 ± 1.55
	Pre-spill 2	1	11.66 ± 2.72	6.23 ± 5.32	6.95 ± 2.45	10.24 ± 0.28	10.85 ± 0.50	11.44 ± 5.31
		2	13.36 ± 1.94	10.93 ± 1.29	9.73 ± 2.08	10.50 ± 0.61	3.91 ± 2.74	13.98 ± 2.14
	Post-spill 1	1	15.64 ± 1.78	6.47 ± 1.20	14.98 ± 4.02	13.76 ± 1.47	15.26 ± 1.41	12.10 ± 2.27
		2	12.04 ± 2.35	14.18 ± 1.55	14.49 ± 1.36	10.77 ± 0.96	5.32 ± 2.50	12.79 ± 1.96
	Post-spill 2	1	14.60 ± 2.56	10.93 ± 2.38	16.29 ± 3.30	11.64 ± 1.35	13.47 ± 3.20	12.19 ± 1.68
		2	13.31 ± 0.13	13.67 ± 2.37	13.95 ± 1.63	9.70 ± 1.32	4.25 ± 1.81	10.68 ± 1.46
	Post-spill 3	1	16.67 ± 1.92	10.67 ± 1.42	20.18 ± 2.39	11.38 ± 0.39	13.07 ± 2.82	11.81 ± 4.65
		2	14.99 ± 3.76	13.01 ± 1.75	15.10 ± 4.71	9.09 ± 1.78	5.98 ± 3.09	10.72 ± 2.25
Microalgae ($cells/m^2 x 10^7$)	Pre-spill 1	1	157.47 ± 54.39	9.21 ± 5.20	44.31 ± 20.14	167.34 ± 70.13	100.76 ± 63.47	57.80 ± 31.41
		2	103.96 ± 29.16	105.85 ± 32.24	77.00 ± 37.00	47.15 ± 36.17	21.29 ± 7.18	176.55 ± 68.56
	Pre-spill 2	1	270.56 ± 130.33	1.65 ± 0.68	20.31	246.02	317.91 ± 97.06	56.64 ± 56.41
		2	332.78 ± 68.84	121.69 ± 12.26	72.50 ± 16.42	126.88	11.76 ± 13.75	240.52 ± 68.55
	Post-spill 1	1	249.68 ± 130.96	15.94 ± 2.32	215.87 ± 83.41	245.13 ± 71.14	205.30 ± 55.65	156.49 ± 42.90
		2	237.11 ± 64.51	268.51 ± 79.21	171.21 ± 26.98	146.30 ± 30.31	21.79 ± 12.68	169.18 ± 34.96
	Post-spill 2	1	365.27 ± 9.37	113.44 ± 76.33	261.60 ± 18.00	267.40	228.00 ± 26.06	175.96 ± 59.04
		2	384.71 ± 83.81	255.49 ± 10.23	205.19 ± 2.16	111.60 ± 30.82	20.55 ± 11.42	238.18 ± 56.31
	Post-spill 3	1	254.37 ± 15.07	169.84 ± 35.17	359.56 ± 78.67	246.17 ± 47.04	236.99 ± 82.82	229.50 ± 5.18
		2	280.22 ± 13.65	205.11 ± 34.07	322.80 ± 116.94	167.82 ± 51.76	51.34 ± 41.42	185.78 ± 36.85
Light ($Watt-h/m^2$)	Pre-spill 1	1	–	–	–	–	–	–
		2	–	–	–	–	–	–
	Pre-spill 2	1	86.10	21.50	34.28	75.41	59.26	36.49
		2	117.59	86.10	47.29	73.32	17.31	64.03
	Post-spill 1	1	108.41	24.40	23.01	82.15	56.82	84.13
		2	106.67	79.25	49.39	71.81	14.29	67.63
	Post-spill 2	1	82.85	22.89	36.95	94.45	51.71	62.75
		2	103.30	65.30	57.29	61.01	12.20	77.16
	Post-spill 3	1	80.53	20.45	34.74	72.97	38.81	53.57
		2	121.66	72.39	56.47	61.59	16.97	90.40

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[1] Oil treatments were applied on 23 and 24 May 1982.

[2] Unweathered Lagomedio crude oil.

[3] 0.45 μm filter.

assimilation of DOC by bacteria. Dissolved organic carbon was separated using 0.45 µm silver filters and thus includes any particles <0.45 µm (e.g. bacteria); details of DOC techniques and results are discussed in a later section. We attempted to separate carbon uptake by algae and bacteria by filtering separate 100 mL subsamples through 3.0 µm and 0.45 µm cellulose acetate filters. Particulate radiocarbon taken up by algae was estimated as radioactivity retained on 3.0 µm filters, and radiocarbon in bacteria was estimated as the difference between radioactivity retained on 0.45 µm and 3.0 µm filters (i.e. $^{14}C_{.45} - ^{14}C_{3.0}$). A correction factor for small microalgae (<3.0 µm) was obtained by repeating the differential filtration procedure with 50 mL subsamples and measuring chlorophyll a and particulate organic carbon (POC).

The results of paired comparisons for all control incubations of ice algae where both filter types were used (Periods 1, 3 and 5) are as follows:

	Productivity	Chlorophyll a	POC
subsample volume	100 mL	50 mL	50 mL
filter difference	0.45 < 3.0	0.45 = 3.0	0.45 = 3.0
P	P<0.01	P>0.5	P>0.1
t	3.098	0.269	1.616
df	41	54	17

Ice algal biomass (chlorophyll a and POC) did not differ significantly between the two filter types in spite of the difference in pore size. This may indicate that microalgae and bacteria <3.0 µm were not abundant in the under-ice community. It is also possible that filters became clogged because of the high algal concentrations, resulting in no effective difference in pore size between the two types of filter.

The difference in productivity data between filter types (average of 21% more radioactive carbon on 3.0 µm filters than on 0.45 µm filters) is less easy to interpret. It is possible that this difference resulted from the higher volume of sample filtered for ^{14}C determinations (100 mL) than for biomass determinations (50 mL); it has previously been reported that damage to algal cells and loss of cell contents through filters increases with sample volume (Arthur and Rigler 1967; Carpenter and Lively 1980; Mague et al. 1980). It is not clear, however, why loss of cell contents would be greater for the filters with smaller pore size. All data reported in the following sections are based on samples from the smaller (0.45 µm) filters, which are in more common use, but it should be pointed out that the reported values for particulate carbon fixation by ice algae may underestimate actual under-ice productivity.

Ice Algal Biomass

The distribution of chlorophyll a in the bottom layer of ice, like cell densities, was relatively even on a small scale (Table 7). Variation among locations and periods was also relatively low, unlike data on cell densities. Mean chlorophyll a concentrations in control samples varied from 3.4 to 16.7 mg/m^2; single sample minimum and maximum values were 0.64 and 23.20 mg/m^2, respectively. Mean chlorophyll concentrations increased progressively throughout the 1982 study period, from 9.1 ± 3.3 mg/m^2 (n = 42) on 18-19 May to 15.7 ± 3.0 mg/m^2 (n = 7 control samples) or 12.8 ± 4.5 mg/m^2 (n = 42; all treatments) on 1-2 June. Concentrations were very similar at Cape Hatt in 1981: chlorophyll concentrations in the bottom layer of ice increased from 6.6 ± 2.0 mg/m^2 (n = 14) on 16 May to 10.9 ± 0.6 mg/m^2 (n = 4) on 30 May.

Ice algal biomass (as estimated by chlorophyll concentration) at Cape Hatt during spring 1981 and 1982 was comparable to biomasses reported for May and June in a number of other arctic locations: Jones Sound (3.0-23.0 mg/m^2; Apollonio 1965); Barrow, Alaska (3.0-30.5 mg/m^2; Clasby et al. 1973); and Robeson Channel and Barrow Strait (0.6-12.5 mg/m^2; Dunbar and Acreman 1980). Considerably higher concentrations were found at fast ice stations in Pond Inlet (17.6-182.6 mg/m^2; Cross 1980, 1982a). Differences in chlorophyll concentrations are likely a result of differences in the timing of the spring bloom or differences in snow cover. The lowest mean biomass reported for Pond Inlet was at the station with the highest mean snow depth (15.8 cm), and a significant negative correlation between snow depth and biomass was found at some stations (Cross 1982a). An inverse relationship between ice chlorophyll and snow depth has also been observed by Alexander et al. (1974).

Carbon to chlorophyll a ratios in control samples ranged from 12.6 to 40.8 (overall mean of 21.1 ± SD 8.8; n = 22). The ratio increased during the study period, from 16.0 ± 2.3 (n = 14) during 15-18 May to 30.0 ± 9.1 (n = 8) during 26 May-2 June. Carbon to chlorophyll ratios for ice algae at Cape Hatt are near the lower end of the range of 20 to 200 suggested for mixed phytoplankton populations (see Raymont 1980, p. 90). There are no previous data of this kind on arctic ice algae, but our results are similar to those of Bunt and Lee (1970), who reported a range of 24 to 59 in carbon to chlorophyll ratios in antarctic ice algae.

Ice Algal Productivity

Ice algal productivity rates reported herein are based on differences between light and dark incubation chambers in the amount of radiocarbon retained on 0.45 um cellulose triacetate filters. All incubations were carried out around noon for 2-3 h periods. Sky conditions varied during incubation periods and from day to day, and the resultant daily values of surface light during incubations ranged from approximately 13 000 to 20,000 watt-h/m^2. Variation in the amount of light reaching the bottom of the ice included not only a temporal component resulting from changes in surface light, but also a spatial component: percent transmission through the ice and snow, measured within each enclosure, varied from 0.11-0.77%. Spatial variability was likely the result of variable snow cover. Snow depths, measured at the surface in the estimated locations of the under-ice enclosures, were from 8.5 to 30.6 cm. The estimated amount of light reaching each enclosure during each incubation is given in Table 7. These values varied over an order of magnitude, from 12.2 to 121.7 watt-h/m^2.

Ice algal productivity increased with increasing light over the range of conditions encountered (Fig. 10). There was no evidence of photosynthetic inhibition at the highest light levels (approximately 120 watt-h/m^2 in a 2-3 h period). Productivity rates were near zero at the lowest light levels (approximately 20 watt-h/m^2; Fig. 10).

Productivity of ice algae varied considerably among locations (enclosures) and periods: mean productivity rates in controls were from near zero to 2.95 mgC/m^2.h (Table 7). The lowest productivity rates were

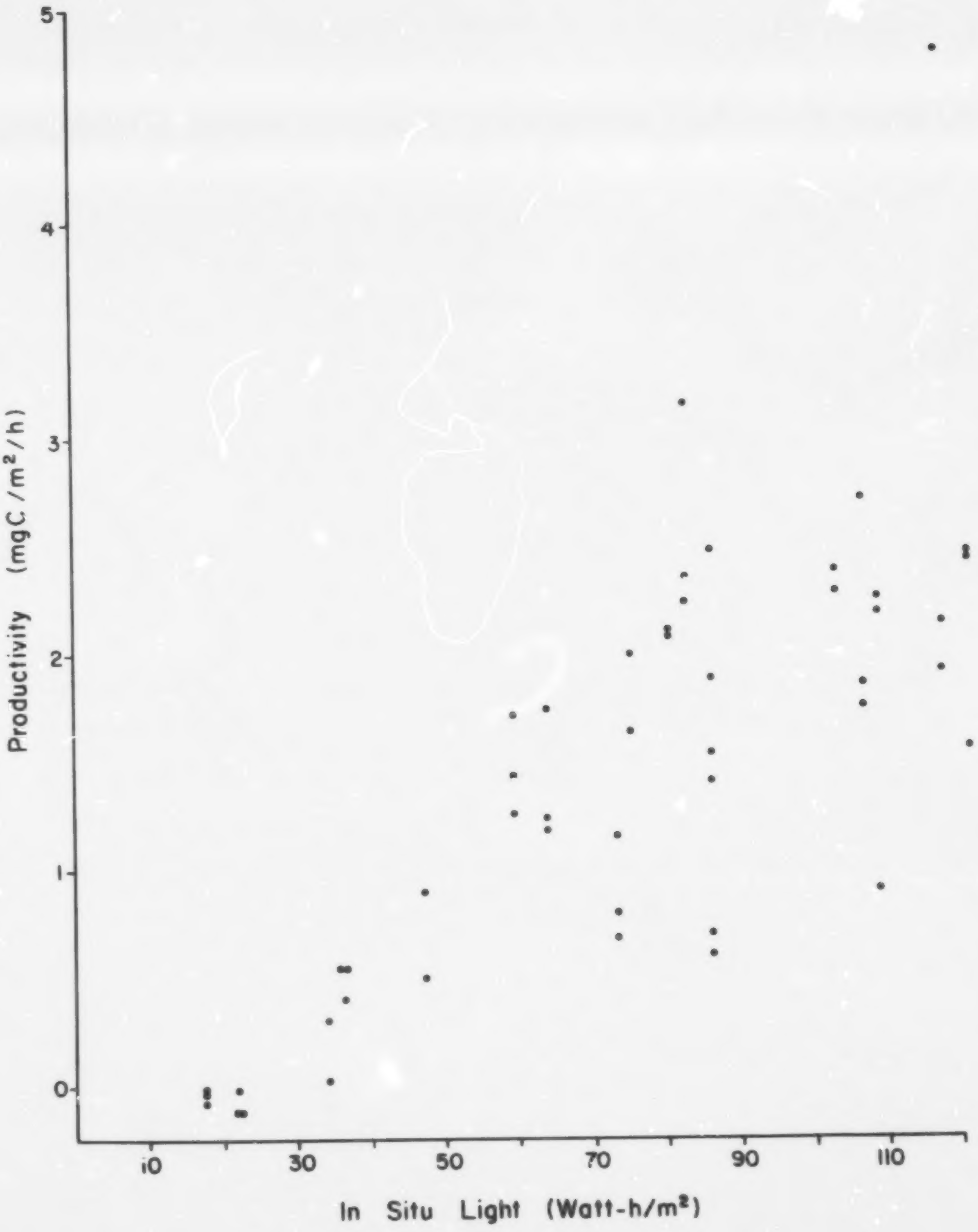

Figure 10. Ice algal productivity (mgC/m^2.h) vs. In situ light (watt-h/m^2) at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982. Each point is the productivity rate calculated for one control incubation; one light measurement was made for each set of 2 or 3 productivity rates.

obtained from enclosures with the lowest recorded light values, e.g., the 'oil' enclosure at Location 1 and the 'BP 1100 WD + oil' enclosure at Location 2 (Table 7). Productivity in control samples increased progressively from 18-19 May (0.85 ± 0.75 mg C/m^2.h; n = 31) to 28-29 May (2.48 ± 0.38 mg C/m^2.h; n = 5), and decreased slightly by 1-2 June to 2.13 ± 0.36 mgC/m^2.h (n = 5). Increased productivity was likely related to increased chlorophyll a concentrations; however, productivity per unit chlorophyll in control samples also increased progressively from 18-19 May to 28-29 May (0.08 to 0.19 mg C/mg Chl a.h), and decreased by 1-2 June (0.14 mg C/mg Chl a.h).

Productivity rates at Cape Hatt were similar in 1981 and 1982. Mean productivity in 1981 varied from 0.26 ± 0.07 to 3.34 ± 1.96 mgC/m^2.h (n = 5 in each case), but there was no apparent increase or decrease over the study period (Cross 1982b). Data from Cape Hatt are also comparable to those of Clasby et al. (1973) at Barrow, Alaska, who reported mean productivity values between 4 and 4.5 mgC/m^2.h on 6 and 21 May, and values between 1 and 1.5 mgC/m^2.h between 25 May and 5 June. It appears that the under-ice algal bloom, and concomitant high productivity, had begun to decline earlier at Barrow in 1972 and possibly at Cape Hatt in 1982, than at Cape Hatt in 1981.

Dissolved Organic Carbon

Productivity rates of dissolved organic carbon (DOC) reported herein are based on the same samples (incubation chambers) and methods of calculation used to estimate particulate radiocarbon productivity. Data presented below include only control samples: all enclosures on 18-19 May, and control enclosures only on 26-27 May and 1-2 June. Radioactivity in DOC was measured in filtrates of subsamples filtered through 0.45 µm silver filters, and purged of inorganic radiocarbon by acidification and aeration. Cell rupture during filtration was avoided by the use of small (20 mL) sample volumes and low (<120 mm Hg) vacuum pressures (see Mague et al. 1980). Other sources of error in $DO^{14}C$ determinations were discussed by Sharp (1977): organic contamination of the innoculum and incomplete removal of inorganic radiocarbon from filtrates. The low levels of $DO^{14}C$ observed in 'controls' (e.g., dark incubations; see below) in the present study, however, and the subtraction of dark values from light values in productivity calculations, eliminates uncertainty associated with these sources of error.

Following 2-3 h incubations at Cape Hatt in 1982, levels of dissolved organic radiocarbon were similar in dark incubation chambers containing ice (+ water), in dark chambers containing water, and in light chambers containing water. DOC productivity rates in dark chambers containing ice (+ water) and water, respectively, were 0.201 ± SD 0.093 $mgC/m^2.h$ (n = 15) and 0.181 ± 0.095 $mgC/m^2.h$ (= 1.185 $mgC/m^3.h$; n = 6). After correction for dark values, DOC productivity in light chambers containing near-ice water was very low: 0.025 ± 0.709 $mgC/m^3.h$ (n = 7). In contrast, mean DOC productivity in light chambers containing ice was very high: 3.25 ± 2.86 $mgC/m^2.h$ (n = 41). DOC productivity by ice algae, like particulate carbon productivity, varied considerably among enclosures (0.13 to 9.33 $mgC/m^2.h$). Dissolved and particulate carbon productivity rates were highly correlated (r = 0.926; P<0.0001; n = 41). On average, DOC accounted for 70.5% of total (dissolved + particulate) production. This percentage is near the upper end of the range of values previously reported in coastal and oceanic waters (see Sharp 1977 for a review; Smith et al. 1977; Lancelot 1979; Larsson and Hagström 1979, 1982; Mague et al. 1980; Sellner 1981; Wolter 1982; Jensen 1983). To our knowledge, DOC production by ice algae has not previously been reported.

There are several possible sources of the dissolved organic carbon. Inorganic radiocarbon fixed by algae can be released into the medium in dissolved or colloidal form in several ways: active release of photosynthetic products by healthy algae (Fogg 1977), lysis of plant cells through various means (see Cole et al. 1982), degradation of non-living plankton (Sharp 1977), losses associated with mechanical breakage of cells during grazing (Lampert 1978), and excretion by grazers that have consumed labeled algae. The release of significant amounts of DOC by healthy algae has been disputed (Sharp 1977), but evidence to the contrary is still convincing (Fogg 1977; Sellner 1981; Larsson and Hagström 1982; Wolter 1982; Jensen 1983).

Regardless of the mechanism of DOC release, however, dissolved organic radiocarbon present in the medium was originally fixed by algae and must be included in our estimates of productivity. Thus mean ice algal productivity (particulate + dissolved) was 4.39 ± 3.69 $mgC/m^2.h$ (n = 41) over the range of light levels studied at Cape Hatt in May 1982. The highest productivity rate measured (single sample) was 12.7 $mgC/m^2.h$. If high DOC production is characteristic of the ice algal community, previous reports on particulate carbon fixation (e.g., Clasby et al. 1973; Cross 1982b) may have underestimated ice algae productivity to a significant extent. Even higher productivity rates would be expected in areas where, unlike the present study area, ice algal biomass was very high (e.g., Pond Inlet in 1979; Cross 1980, 1982a).

The fate of dissolved organic carbon produced by ice algae, and in particular its contribution towards the transfer of energy to higher trophic levels, is not known. Bacteria may be important in the sea ice community as consumers of DOC released by algae and as a particulate food source for protozoans and metazoans. Bacteria are common and often abundant in sea ice (Horner 1976), and extremely high bacterial activity was found in the under-ice community at Cape Hatt in May 1981 (J. Bunch, unpubl. data). At Barrow, Alaska, uptake of labeled dissolved organic substances by the sea ice community was almost exclusively by bacteria (Horner and Alexander 1972b). In other marine habitats, bacterial uptake of photosynthetically produced DOC can be as high as 90% (e.g., Wolter 1982; Jensen 1983). Attempts to measure bacterial uptake in the present study were not successful (see 'Evaluation of Filtration Techniques' section), but any radiocarbon present in bacteria <0.45 µm in size would be included in our estimates of dissolved organic carbon productivity.

Oil Effects

Impingement of unweathered oil and dispersed oil onto the under-ice surface would probably cause some immediate mortality of under-ice algae. Inhibition of photosynthesis in ice algae was observed at the highest levels of oil and dispersed oil tested in 1981 (Cross 1982b). There may also be some subsequent recovery of the ice algae as the oil moves into the ice or as the dispersed oil is removed by currents and dilution. The extent and rate of this mortality and subsequent recovery are as yet unknown.

In the present study, standing stocks and productivity of under-ice algae were measured before and after treatment with crude oil (Venezuela Lagomedio), solidified oil (BP treatment), oil mixed with each of three dispersants (Corexit 9527, BP 1100 WD and BP CTD), and no oil (control). Dispersed oil, in concentrations between 5.8 and 36.5 ppm, was contained within enclosures beneath the ice for approximately five hours. Oil and solidified oil remained in the enclosures on the under-ice surface during post-treatment sampling periods, and sampling was carried out within the enclosures but not directly in the oiled areas. Oil concentrations in the water within enclosures containing oil and solidified oil, measured 5 h after treatment, were similar to control values (see 'Methods').

During the first year of studies at Cape Hatt, analysis of covariance with _in situ_ light intensity as the covariate proved useful in taking variability due to light into account before testing for differences among periods or treatment levels (Cross 1982b). The larger number of replicates and treatments used in the present study, however, together with other changes in the study design, resulted in the measurement of light for each enclosure (i.e. for each treatment and location) but not for each replicate. Hence, analysis of covariance was not used. Analysis of variance was applied to data on standing stocks and productivity, and to ratios calculated to standardize for light effects: standing stocks/percent transmission, and productivity/_in situ_ light during incubations. Productivity per unit of chlorophyll and productivity per unit chlorophyll per unit light were also subjected to analysis of variance.

Three factor analysis of variance (period, treatment and location) were carried out, but significant three way interactions necessitated the use of two factor ANOVAs (period, treatment) for each of the two locations. The results of these analyses for eight variables are given in Table 8. Most interactions between period and treatment factors were significant (13 of 16 cases). In these cases, the significant interaction terms means that period-to-period variation was not consistent among treatments, indicating the possibility of an oil effect. However, other factors besides the treatment could also lead to significant interaction terms.

To determine whether the significant interactions were attributable to the two enclosures with very low levels of light and productivity, these enclosures (treatments) were excluded from the analyses. Results were very similar to those shown in Table 8. The significance of the period x treatment interaction in the new analyses differed from that in Table 8 in only two cases: when low-light treatments were excluded, the interaction was non-significant for productivity per unit chlorophyll per unit light only in Location 2, and was marginally significant ($P = 0.028$) for chlorophyll concentration over percent transmission only in Location 2. Hence, the significance of period x treatment interactions (Table 8) was not attributable to effects of low-light conditions.

It was necessary to examine the nature of the period-to-period variability among treatments to determine whether it was consistent with expected oil effects. Expected oil effects would include (1) marked deleterious effects of oil relative to controls, (2) immediate effects in dispersed oil treatments, followed by recovery, (3) delayed effects in oil or

Table 8. Results of analysis of variance for standing stocks and productivity of under-ice algae at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982. F-values are shown with significance levels (ns = $P>0.05$; * $P\le0.05$; ** $P\le0.01$; *** $P\le0.001$).

Variable	Location	Source of Variation			Degrees of Freedom[1]
		Period	Treatment	Period x Treatment	
Productivity (P)	1	16.46 ***	45.75 ***	3.25 ***	4,5,20/53
	2	7.01 ***	33.68 ***	2.38 **	4,5,20/54
Chlorophyll *a* (B)	1	17.98 ***	11.78 ***	2.56 **	4,5,20/76
	2	2.69 *	33.58 ***	1.47 ns	4,5,20/75
Algal density (D)	1	19.72 ***	17.77 ***	2.39 **	4,5,20/56
	2	19.42 ***	35.90 ***	4.26 ***	4,5,20/58
P/B	1	8.49 ***	34.24 ***	3.19 ***	4,5,20/52
	2	8.43 ***	38.75 ***	3.01 ***	4,5,20/52
P/Light[2]	1	23.60 ***	15.55 ***	5.77 ***	3,5,15/44
	2	8.71 ***	22.34 ***	1.45 ns	3,5,15/44
P/B/Light[2]	1	14.02 ***	9.80 ***	6.07 ***	3,5,15/43
	2	14.15 ***	20.40 ***	3.01 **	3,5,15/43
B/Percent transmission[2]	1	1.13 ns	14.35 ***	2.48 **	3,5,15/61
	2	4.81 **	26.05 ***	1.07 ns	3,5,15/60
D/Percent transmission[2]	1	8.11 ***	13.27 ***	4.11 ***	3,5,15/41
	2	2.65 ns	9.52 ***	2.95 **	3,5,15/42

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[1] Degrees of freedom shown are numerator df for period, treatment and period x treatment interaction, followed by denominator df.

[2] All analyses including light or percent transmission exclude data from Period 1, where percent transmission data were not recorded.

solidified oil treatments, and (4) effects in dispersed oil treatments that were consistent with measured oil levels (see 'Methods'), i.e. least in BP CTD; more pronounced in Location 2 than Location 1 for Corexit 9527 and BP 1100 WD. Inspection of the data (Fig. 11) showed little evidence for any of these expected oil effects.

There were no marked deleterious effects of any oil treatment on any of the variables. Decreases in some or all variables from the immediate pre-spill to immediate post-spill periods were evident in some enclosures, (e.g., Corexit + oil, Location 2), but these generally corresponded with decreases in light, and were also evident in the control.

There were no marked immediate effects of dispersed oil treatments, nor was there any evidence of recovery in later post-spill periods. Differences among dispersants or between locations were not consistent with measured oil concentrations.

Inspection of the data for oil and solidified oil treatments indicated the possibility of a stimulation effect of these treatments on the biomass and productivity of under-ice algae. Progressive (period-to-period) increases in biological variables were not common in any treatment except the solidified oil and, to a lesser extent, untreated oil treatments. This progressive increase is not clearly related to increases in light, particularly in the case of the solidified oil treatment. In some cases, however, increases in biological variables at these locations were also apparent between the two pre-spill periods. Increases in biomass and productivity are typical of under-ice algae during the spring before the peak

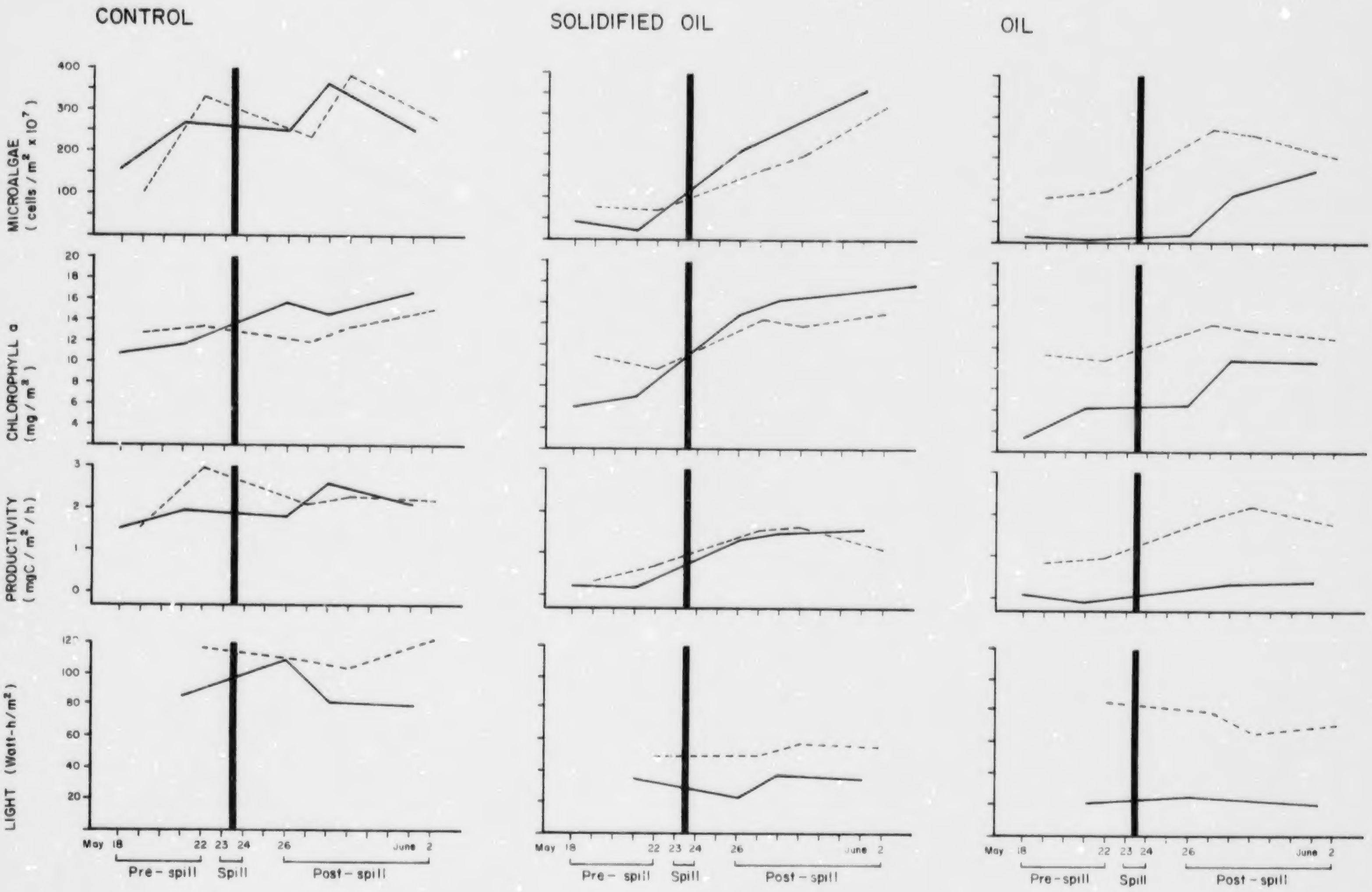

FIGURE 11. Under-ice productivity, chlorophyll *a*, microalgal density and *in situ* light data in two locations at Cape Hatt, Baffin Island, during 18 May-2 June 1982. Location 1 is represented by a uniform line; Location 2 is represented by a broken line. Values for each date are means of 3-4 replicate ice core samples (10 cm diameter).

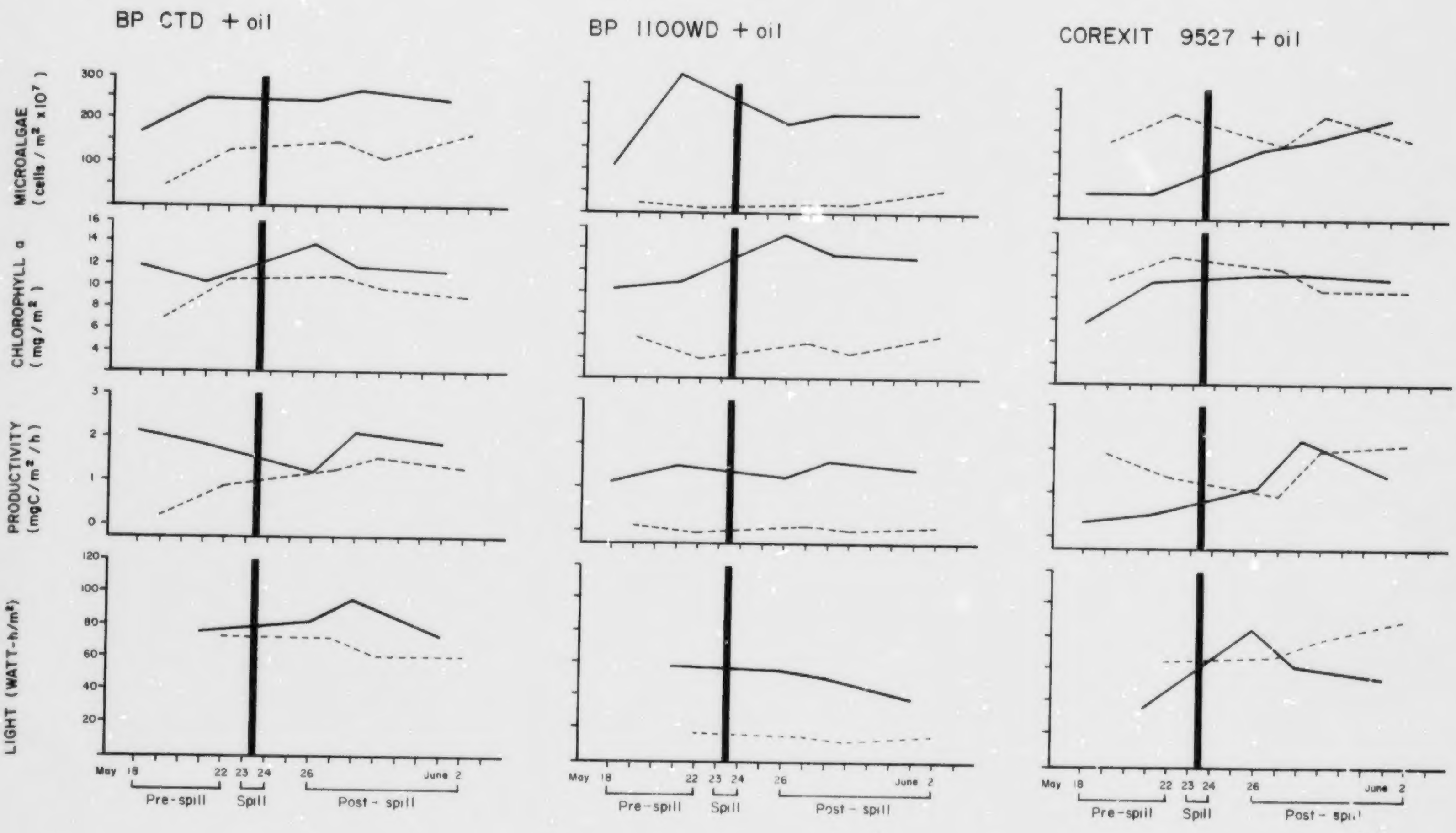

FIGURE 11. continued.

of the bloom (Horner and Alexander 1972; Clasby et al. 1973) and were also evident in Cape Hatt during May 1981 (Cross 1982b). Overall, productivity and standing stocks in control samples increased during the 1982 study period (see above). Differences among enclosures (treatments) in the nature of the increases may also be related to snow conditions, and in particular, changes in snow depth that occurred immediately before the study period.

Inhibition of photosynthesis of ice algae was observed at the highest levels of oil and dispersed oil tested at Cape Hatt in 1981 (10,000 ppm; Cross 1982b). At this level, dispersed oil apparently had a larger effect (total suppression of productivity) than did undispersed oil, but even in the latter case productivity was much reduced from control levels.

Hsiao et al. (1978) reported oil effects on productivity of arctic marine phytoplankton in oil-seawater dispersions at concentrations as low as 10 ppm; at concentrations between 43 and 147 ppm values were 20 to 40% of control productivity, depending on type of oil. Similar results on diatom growth were obtained when oil was added directly to algal cultures to give nominal concentrations between 10 and 10,000 ppm (Hsiao 1978). After 10 day's exposure, diatom growth was reduced at all concentrations for all oils tested, but the highest concentration was lethal only to some combination of species and oils.

In the present study, we attempted to create realistic scenarios for the impingement of oil onto the under-ice surface: low concentrations of dispersed oil contacting the ice for a short period of time, and untreated oil and solidified oil remaining in place on the under-ice surface. Analyses and inspection of the data showed considerable spatial and temporal variability in productivity and standing stocks of under-ice algae, but there was little evidence for any of the expected oil effects.

Under-ice Meiofaunal Communities

In this section we examine the effects of *in situ* applications of oil and chemically treated oil on the distribution of major meiofaunal groups. Meiofauna are defined as those invertebrates falling within the size range 40 µm to 1 mm, after Elmgren (1976). A description of abundance, species composition and spatial and temporal variability in the meiofaunal community is based on control samples collected in both pre-spill and post-spill periods at the productivity study site (Bay 13) at Cape Hatt. The distribution of under-ice meiofauna in the four BIOS study bays (Bays 7, 9, 10 and 11) at two times in May 1982 is also described.

Species Composition

The under-ice meiofauna collected at Cape Hatt during 18 May-2 June 1982 included copepods, nematodes, polychaete larvae, rotifers and gastropod veligers. Copepods, the numerically dominant taxon, comprised 92.3% of total numbers collected during the study. Nematodes and polychaetes made up 4.0% and 3.2% of total numbers, respectively. Rotifers and gastropod veligers were also present in very small numbers. Thomson et al. (1978) also reported that copepods were predominant (79.0% of total meiofaunal) in the under-ice surface in Brentford Bay, Boothia Peninsula. Elsewhere, nematodes are usually the most abundant group of under-ice meiofauna (Carey and Montagna 1982; Cross 1982a; Grainger and Hsiao 1982; Kern and Carey 1983).

During 18 May-2 June 1982, cyclopoid and harpacticoid copepods comprised 83.2% and 16.3%, respectively, of the ice copepod fauna (Table 9). Calanoid copepods were only represented by nauplii, and accounted for the remainder of total numbers. A total of six species of cyclopoid and harpacticoid copepods were collected in systematic samples from the under-ice surface. *Cyclopina schneideri* and cyclopoid copepodites (mostly *Cyclopina* sp.) were present in most samples, and together comprised over 80% of total copepods identified. The harpacticoid copepod *Tisbe furcata* occurred in all control ice samples, and represented an average of 12.2% of total copepod numbers. Other cyclopoids (*Oithona similis* and *Oncaea minuta*) and harpacticoids (*Microsetella* sp. and *Dactylopodia vulgaris*) were rare, both in terms of abundance and occurrence; each contributed less than 1% to total copepod numbers during the study. One solitary individual of the species *Harpacticus superflexus* was present in a non-quantitative sample.

Low species diversity of copepods is apparently characteristic of the soft bottom layer of the ice. The genera *Cyclopina*, *Harpacticus*, *Oithona*, *Oncaea* and *Tisbe* have been consistently found in under-ice habitats of arctic and antarctic regions (Andriashev 1968; Thomson et al. 1978; Cross 1982a; Grainger and Hsiao 1982; Kern and Carey 1983).

Abundance

Total meiofaunal densities at the productivity site in Bay 13 (control samples only) averaged approximately 54,000 individuals/m^2; copepods alone contributed about 50,000 ind./m^2 (Table 10). Water samples taken just below the ice-water interface included all major ice-associated taxa,

Table 9. Species composition of under-ice copepods in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[1]. Data are based on 10 cm diameter ice cores.

Period →	Pre-spill 1		Pre-spill 2		Post-spill 1		Post-spill 2		Post-spill 3	
Date →	18-19 May		21-22 May		26-27 May		28-29 May		1-2 June	
n →	21		21		4		3		4	
Taxon	% of numbers	% occurrence	% of numbers	% occurrence	% of numbers	% occurrence	% of numbers	% occurrence	% of numbers	% occurrence
Copepoda										
Cyclopoida (total)[2]	(83.3)		(85.5)		(73.5)		(77.3)		(72.7)	
Cyclopina schneideri	12.5	86	24.3	100	44.6	100	49.8	100	51.4	100
Oithona similis	0.2	14	<0.1	5	-	-	0.2	67	-	-
Oithona copepodite	-	-	0.1	19	-	-	-	-	-	-
Oncaea minuta	0.1	10	<0.1	10	-	-	0.1	33	-	-
Oncaea copepodite	0.1	10	0.1	29	0.6	75	0.5	67	0.2	25
Unidentified copepodite[3]	67.4	100	58.0	100	26.1	100	24.8	100	19.1	100
Nauplii	2.7	81	2.3	100	1.1	100	1.1	67	1.0	50
Harpacticoida (total)	(16.2)		(14.1)		(25.9)		(21.9)		(27.1)	
Tisbe furcata	13.2	100	10.5	100	18.0	100	15.6	100	19.1	100
Tisbe copepodite	2.0	76	1.4	86	2.5	100	1.6	100	3.9	100
Microsetella sp.	-	-	0.1	19	0.3	25	-	-	-	-
Microsetella copepodite	-	-	-	-	-	-	0.3	67	0.4	50
Dactylopodia vulgaris	0.1	5	0.1	14	0.1	25	0.2	33	0.4	50
Unidentified copepodite	-	-	0.1	10	0.5	25	-	-	-	-
Nauplii	0.9	48	2.0	91	4.5	100	4.2	100	3.3	75
Calanoida										
Nauplii	0.5	38	0.4	81	0.6	75	0.8	100	0.2	25
Total number identified	2,521		8,546		799		1,165		508	

[1] Data from only pre-spill periods and control treatments in post-spill periods are included.
[2] Total % includes unidentified adults.
[3] Majority identified as *Cyclopina* sp.

Table 10. Density (nos./$m^2 x 10^3$) of major meiofaunal groups on the under-ice surface in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[1]. Data are expressed as mean ± SD and are based on 10 cm diameter ice cores.

Taxon		Period				
		Pre-spill 1	Pre-spill 2	Post-spill 1	Post-spill 2	Post-spill 3
	Date →	18-19 May	21-22 May	26-27 May	28-29 May	1-2 June
	n[2] →	21[43]	21[40]	4[8]	3[6]	4[7]
Copepoda (total)		(43.55 ± 24.92)	(54.67 ± 27.77)	(62.72 ± 16.38)	(52.36 ± 17.57)	(48.62 ± 13.65)
Cyclopoida (total)		(38.23 ± 19.17)	(51.64 ± 21.77)	(49.57 ± 13.92)	(44.85 ± 16.47)	(34.03 ± 13.16)
Adult		6.05 ± 3.89	15.10 ± 8.01	30.80 ± 11.29	29.56 ± 15.61	24.54 ± 11.08
Copepodite		30.96 ± 16.25	35.16 ± 16.05	18.01 ± 4.16	14.65 ± 2.76	8.99 ± 1.96
Nauplii		1.22 ± 0.90	1.38 ± 0.75	0.77 ± 0.47	0.64 ± 0.65	0.50 ± 0.81
Harpacticoida (total)		(7.45 ± 5.43)	(8.50 ± 6.93)	(17.41 ± 4.02)	(12.74 ± 3.90)	(12.06 ± 4.03)
Adult		6.10 ± 5.13	5.38 ± 6.04	12.36 ± 3.21	9.19 ± 3.87	8.90 ± 2.89
Copepodite		0.93 ± 1.23	0.89 ± 1.04	2.09 ± 0.88	1.14 ± 0.42	1.82 ± 1.41
Nauplii		0.42 ± 0.66	1.22 ± 0.95	3.03 ± 1.15	2.41 ± 1.43	1.34 ± 1.64
Calanoida						
Nauplii		0.24 ± 0.35	0.25 ± 0.17	0.43 ± 0.35	0.45 ± 0.27	0.08 ± 0.15
Nematoda		1.11 ± 1.17	1.55 ± 1.32	3.44 ± 1.08	4.40 ± 2.89	4.92 ± 2.26
Polychaeta		1.15 ± 1.14	1.87 ± 1.05	2.26 ± 1.53	2.11 ± 0.97	1.70 ± 0.63
Total nos./$m^2 x 10^3$		45.81	58.09	68.42	58.87	55.24

[1] Data from only pre-spill periods and control treatments in post-spill periods are included.

[2] Numbers of samples are shown for copepod sub-group followed by major groups [in parentheses].

but their abundance was much lower than in the ice above: about 13,000 individuals/m^3 or 2,000 ind./m^2, based on 184 individuals in 24 control samples. Most of the meiofauna in ice (+ water) samples, therefore, occurred in the bottom layer of ice.

Under-ice copepod densities were higher, and nematode densities generally lower, than those previously reported in arctic and sub-arctic waters during May:

Location	Sample size	Mean[1] densities (no./m^2) total	copepod	nematode	Source
Cape Hatt	104	2500-54,000	2000-50,000	30-1900	Present study
Brenford Bay	16	17,000	13,000	2900	Thomson et al. (1978)
Pond Inlet	29	300-53,000	100-20,500	0-31,900	Cross (1982a)
Stefansson Sound	9	4,500	800	3500	Carey and Montagna (1982)
Stefansson Sound	33	19,000	6500	8500	Kern and Carey (1983)
Frobisher Bay	-	46,000-326,000	6000-15,000	20,700-293,000	Grainger and Hsiao (1982)

[1] Ranges are for stations within locations, or for data for which means could not be calculated.

Spatial Effects

Meiofauna were relatively evenly distributed on a small scale (i.e. within the 1.2 m^2 enclosures) at the productivity site in Bay 13. The standard deviation was usually much less than the mean for each of the major meiofaunal groups (Appendix F). Variation on a larger scale (among enclosures in Bay 13--Fig. 12; among bays--Table 11) was considerable, and was evident for all meiofaunal groups. Nematodes were the one group for which interactions did not confound the results; differences among enclosures were highly significant ($P<0.001$; Table 12).

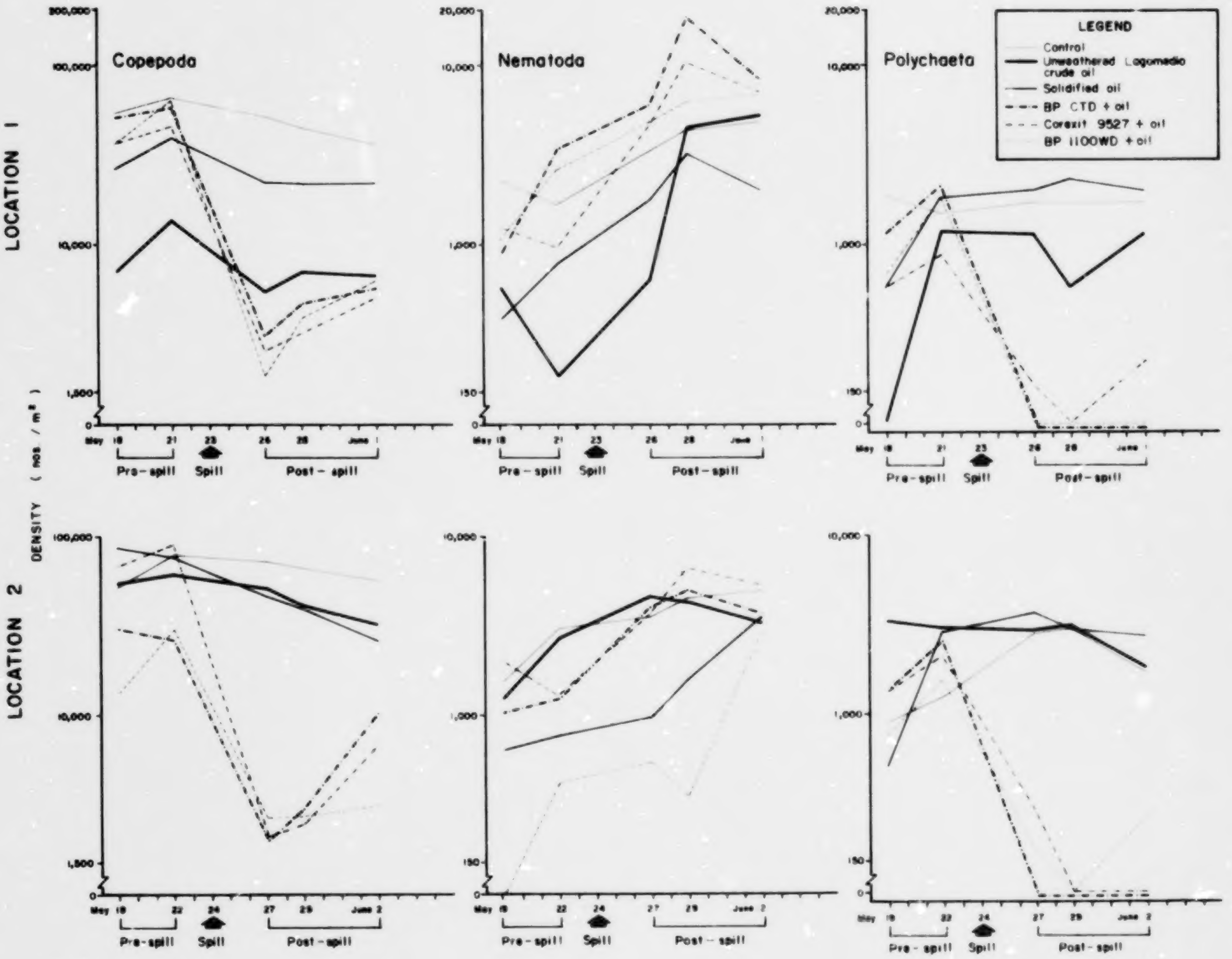

FIGURE 12. Densities of major meiofaunal groups exposed to oil and chemically treated oil on the under-ice surface in two locations at Cape Hatt, Baffin Island, during 18 May-2 June 1982. Values for each date are means of 3-4 replicate ice core samples (10 cm diameter).

Table 11. Density (nos./m^2) of under-ice amphipods, meiofauna and microalgae and snow depth (cm) in four bays[1] at Cape Hatt, Baffin Island, during May 1982. Meiofaunal and microalgal data are based on 5 replicates[2] and amphipod data are based on 16 replicates[3] in each bay and sampling period.

Taxon		Bay 7	Bay 9	Bay 10	Bay 11
		mean ± SD	mean ± SD	mean ± SD	mean ± SD
Microalgae (x10^7)	Early May	196 ± 89	164 ± 99	298 ± 71	84 ± 51
	Late May	361 ± 158	362 ± 69	300 ± 91	121 ± 126
Copepoda	Early May	14,510 ± 6,511	9,333 ± 7,605	11,705 ± 11,807	4,565 ± 4,324
	Late May	9,547 ± 5,914	2,068 ± 560	50,122 ± 18,307	4,115 ± 1,369
Nematoda	Early May	204 ± 264	230 ± 293	490 ± 411	26 ± 57
	Late May	392 ± 428	311 ± 422	289 ± 200	49 ± 67
Polychaeta	Early May	383 ± 239	459 ± 306	1,346 ± 705	2,933 ± 1,265
	Late May	220 ± 305	70 ± 105	265 ± 325	4,446 ± 2,142
Amphipoda	Early May	6 ± 5	3 ± 3	29 ± 24	6 ± 5
	Late May	16 ± 12	6 ± 4	33 ± 26	12 ± 10
Snow depth[4] (cm)	Early May	23.8 ± 4.1	18.7 ± 4.9	10.6 ± 2.5	17.0 ± 6.2
	Early June	20.8 ± 3.9	21.9 ± 5.0	8.8 ± 2.6	19.0 ± 9.2

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release); oil was released in August 1981.

[2] Core samples; 2.5 cm diameter for microalgae, 10 cm diameter for meiofauna.

[3] Net samples covering 4 m^2.

[4] Data are based on 17-21 replicates.

Table 12. Comparison of densities of meiofauna exposed to oil[1] and chemically treated oil[1] on the under-ice surface in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[2]. F-values are shown with significance levels (ns = P>0.05; * P<0.05; ** P<0.01; *** P<0.001). Significance levels are not shown for main effects when the interaction term was significant.

		Source of Variation (df)		
Taxon	Location	Period (4,77)	Treatment (5,77)	Period x Treatment (20,77)
Copepoda	1	42.31	35.14	5.10 ***
	2	28.12	45.99	5.34 ***
Nematoda	1	36.91 ***	11.58 ***	1.60 ns
	2	11.55 ***	12.34 ***	0.87 ns
Polychaeta	1	5.73	15.55	2.91 ***
	2	8.24	20.93	3.32 ***

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[1] Unweathered Lagomedio crude oil.

[2] Oil treatments were applied on 23 and 24 May 1982.

Densities of meiofauna in the BIOS study bays are shown in Table 11 together with corresponding data on snow depths and densities of microalgae and amphipods. No consistent relationships are apparent between any of these variables. In some cases, this may be related to differences in sample types and locations within the bays; meiofauna samples were randomly located, whereas amphipod samples were systematically located and covered much larger areas. The lack of any consistent relationship among groups of meiofauna, however, indicates that a number of different factors are involved and whose effects on meiofaunal distribution differ among the groups.

There are several possible sources of this large scale variability, including snow depth, light and concentrations of microalgae. In all Bay 13 control enclosures taken together (n = 104), light was positively correlated with densities of nematodes ($r = 0.58$; $P<0.001$), copepods ($r = 0.52$; $P<0.001$) and, to a lesser extent, polychaetes ($r = 0.27$; $P<0.01$). Similar correlations were evident between chlorophyll a concentrations and the densities of each of these groups. Light and chlorophyll concentrations were also positively correlated ($r = 0.68$; $P<0.001$). From a correlation analysis of this type it is not possible to identify causal relationships.

Cross (1982a) reported that copepod abundance, but not nematode abundance, was significantly greater in brown ice than in clear ice at one station in Pond Inlet. At another station both nematode and copepod numbers were significantly greater in a dense, loose algal layer under clear ice than in brown ice. Over 92% of the nematodes found by Thomson et al. (1978) in 16 core samples collected in Brentford Bay were in three samples taken under an area of ice that had previously been cleared of snow. At the same time there was no corresponding increase in copepod density or in apparent algal growth. Thus, it is possible that nematode densities are more strongly influenced by light, and copepod densities by algal concentrations.

Other factors may also influence the distribution of meiofauna. Carey and Montagna (1982) suggest that ice meiofauna may be recruited from benthic or pelagic habitats by means of vertical migration or advective forces. Hence, their distribution and abundance may also be influenced by water depth and prevailing currents. Differences among groups would be expected for swimming (copepods and some polychaetes) and non-swimming (nematodes and other polychaetes) forms.

Warwick (1981b) points out that meiobenthic nematodes are rarely or never found in stomach contents of benthic predators, whereas meiobenthic copepods are known to form a significant item in their diets. Small copepods of the antarctic ice fauna were found in fingerlings of *Trematomus borchgrevinki* by Andriashev (1968), and ice copepods dominated the diet of arctic cod near the Pond Inlet ice edge (Bradstreet and Cross 1982); in each case nematodes were not mentioned. Predation may, therefore, affect ice copepod densities, but this would not appear to be the case for nematodes.

Temporal Effects

Results of two-factor analyses of variance (treatments and periods) for densities of meiofaunal groups in Bay 13 were unambiguous only in the case of nematodes (Table 12). In both locations, nematode densities showed a highly significant ($P \leq 0.001$) period effect; mean density in control samples increased from 1100 individuals/m^2 on 18 May to 4900 ind./m^2 on 2 June 1982 (Fig. 12). Nematode densities also increased over the same time period in three of the four BIOS study bays. Similar increases in nematode densities during the spring bloom have been reported in Frobisher Bay during 1981 (20,700 to 293,000 ind./m^2; Grainger and Hsiao 1982) and in the Beaufort Sea in 1980 (350 to 25,000 ind./m^2; Kern and Carey 1983).

Copepod and polychaete abundances in control samples from Bay 13 were relatively constant over the study period (Fig. 12). However, this was not true for all particular types of copepods. Cyclopoid copepodites in Bay 13 decreased from 30,900 individuals/m^2 on 18-19 May to 9000 ind./m^2 on 1-2 June. At the same time, cyclopoid adults increased from 6000 to 24,500 ind./m^2 (Table 10). In contrast, harpacticoid copepods showed no obvious temporal variation related to stages of development. In the other four bays, the trends in numbers from early to late May were not consistent among bays or groups (Table 11).

Kern and Carey (1983) reported significant temporal variation in copepod and polychaete densities in the Beaufort Sea during May 1980, but no progressive change was evident in either group. Numbers of both groups decreased substantially between early and late May in Frobisher Bay (Grainger and Hsiao 1982).

Oil Effects

The study design of this component involves five oil treatments plus a control in each of two locations, and two pre-spill and three post-spill sampling periods. Three-factor analyses of variance (locations, treatments, periods) were carried out, but significant interactions involving location precluded unambiguous interpretation of period x treatment interactions and main effects. Therefore, separate two-factor analyses of variance (treatments and periods) were carried out in each of the two locations for each of the three variables: densities of copepods, nematodes and polychaetes. Treatment x period interactions were highly significant ($P<0.001$) for two of these groups, copepods and polychaetes, in each of the locations (Table 12).

Copepod and polychaete densities decreased dramatically between pre-spill and post-spill periods in each of the three dispersed oil treatments in each location; densities in the other three treatments (control, solidified oil and oil) remained relatively constant (Fig. 12). Nematodes were completely unaffected by any of the oil treatments; densities increased throughout the study period in each treatment and in each location (Fig. 12). The observed response in copepods and polychaetes was similar for the three types of dispersants and the two locations, irrespective of the differences in oil concentrations measured within the enclosures (6-37 ppm).

Densities of polychaetes and copepods in dispersed oil treatments increased slightly between post-spill Periods 1 and 3. This increase was more apparent for copepods than for polychaetes, probably indicating a faster recovery rate (Fig. 12). It is not known whether the copepods or polychaetes were killed outright or merely displaced from the ice undersurface. Gyllenberg and Lundqvist (1976) found that 2 pelagic species of copepods exposed to dispersed oil first performed escape movements (period of high activity) and then entered a state of narcosis and sank to the bottom. Ice-associated meiofauna that left the ice would likely be susceptible to benthic predators. In deep water, even if complete recovery occurred in the water column, possibilities for returning to the ice seem remote.

Conflicting evidence has been reported on the effects of oil on meiofauna. Dalla Venezia and Fossato (1977) found that the copepod *Tisbe bulbisetosa* was quite tolerant to a suspension composed of Kuwait oil and Corexit. Boucher (1980) observed that some harpacticoid copepods were unaffected by oil, and some were even attracted to it. Kontogiannis and Barnett (1973), on the other hand, found that oil was toxic to a tide pool copepod, and suggested that resistance to crude oil may change from species to species and from habitat to habitat.

The differences in our results for copepods and nematodes is consistent with a current theory that the ratio of nematodes to copepods is a potentially useful tool in monitoring organic pollution, including oil pollution (Raffaelli and Mason 1981; Warwick 1981a). Coull et al. (1981) argue, however, that the use of this ratio is an oversimplification. Again, conflicting evidence has been reported. McLachlan and Harty (1982) found that dispersed oil was more toxic than fresh oil to all taxa, but that nematodes generally were the least sensitive and oligochaetes the most sensitive. Boucher (1980), on the other hand, found a general decrease in abundance of nematodes in the intertidal zone impacted by the Amoco Cadiz oil spill.

The higher nematode to copepod ratios in areas of the under-ice surface exposed to dispersed oil treatments (Table 13) concur with the postulation of Raffaelli and Mason (1981) and Warwick (1981a). At Cape Hatt, nematode to

Table 13. Nematode to copepod ratios in two locations exposed to oil[1] and chemically treated oil[1] on the under-ice surface in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[2]. Data are based on 4 replicate ice cores (10 cm diameter) for each treatment, location and sampling period.

		Treatment					
Period	Location	Control	Oil[1]	Solidified Oil[1]	BP CTD +Oil[1]	BP 1100WD +Oil[1]	Corexit 9527 +Oil[1]
Pre-spill 1	1	0.042	0.081	0.014	0.017	0.029	0.034
	2	0.029	0.023	0.007	0.035	0.007	0.029
Pre-spill 2	1	0.025	0.013	0.020	0.058	0.042	0.021
	2	0.038	0.044	0.010	0.046	0.014	0.014
Post-spill 1	1	0.064	0.115	0.079	1.933	2.582	1.838
	2	0.049	0.088	0.021	1.964	0.203	1.781
Post-spill 2	1	0.096	0.638	0.147	3.957	1.606	3.179
	2	0.067	0.102	0.040	1.644	0.127	2.667
Post-spill 3	1	0.135	0.782	0.092	1.507	1.102	1.442
	2	0.085	0.100	0.133	0.361	0.954	0.782

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[1] Unweathered Lagomedio crude oil.

[2] Oil treatments were applied on 23 and 24 May 1982.

copepod ratios were low in all study bays in May 1982 (Tables 11 and 13). If this ratio does prove to be a useful indicator of pollution in under-ice communities, the conclusion would follow that the Cape Hatt/Ragged Channel area is a non-polluted environment in spite of the experimental releases of oil carried out in 1981.

In view of the contradictory and limited data available on the effects of oil on meiofauna, however, we must be cautious in using such a simple ratio as a pollution indicator (see Coull et al. 1981). In addition, too few data are available concerning the composition of the under-ice meiofaunal community under pristine conditions, and on natural factors affecting the distributions of copepods and nematodes.

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Appendix A. Numbers of samples of variables for productivity component of the under-ice study, at Cape Hatt, Baffin Island, during 18 May-2 June 1982. Ice samples[1], followed by near-ice water samples[2] (in parentheses) are shown.

Variable		Pre-spill Periods		Post-spill Periods			Total	
	Date ->	1 18-19 May	2 21-22 May	1 26-27 May	2 28-29 May	3 1-2 June	Ice	Water
Inorganic nutrients - post incubation		24 (6)		24 (6)		24 (6)	72	18
- pre incubation		13		2		2	17	
Chlorophyll a, phaeopigments	>.45 µm	48 (12)	48 (12)	48 (12)	48 (12)	48 (12)	240	60
	>3 µm	48 (12)		48 (12)		48 (12)	144	36
Particulate carbon	>.45 µm	24 (6)		24 (6)		24 (6)	72	18
	>3 µm	24 (6)		24 (6)		24 (6)	72	18
Microalgae - numbers		24 (6)	24 (6)	24 (6)	24 (6)	24 (6)	120	30
- species		24 (6)		24 (6)		24 (6)	72	18
Meiofauna - numbers, groups		24 (6)	24 (6)	24 (6)	24 (6)	24 (6)	120	30
- species		24 (6)	24 (6)	24 (6)	24 (6)	24 (6)	120	30
^{14}C activity - 'Algae'	>3 µm	48 (12)		48 (12)		48 (12)	144	36
Algae + Bacteria	>.45 µm	48 (12)	48 (12)	48 (12)	48 (12)	48 (12)	240	60
Dissolved organic		48 (12)		48 (12)		48 (12)	144	36
Meiofauna (groups)		48 (12)		48 (12)		48 (12)	144	36

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[1] Sample numbers are evenly distributed among treatments and locations (6 x 2 per period); in a few cases the number of samples per period/treatment/location (usually 3 or 4 depending on variable) was reduced by 1 or 2.

[2] 1 or 2 replicates in each treatment and period: BP CTD +oil, oil, solidified oil (Location 1) and Corexit 9527 +oil, BP 1100WD +oil, control (Location 2).

Appendix B . Density (nos./m^2) of dominant amphipods on the under-ice surface in four bays[1] at Cape Hatt, Baffin Island, during May 1981 and 1982[2]. Data are based on 10-16 samples, each covering 4 m^2, in each bay and sampling period.

Taxon	Year	Bay 7		Bay 9		Bay 10		Bay 11	
		Early May mean ± SD	Late May mean ± SD	Early May mean ± SD	Late May mean ± SD	Early May mean ± SD	Late May mean ± SD	Early May mean ± SD	Late May mean ± SD
Weyprechtia pinguis	1981	-	-	1.44 ± 0.98	6.70 ± 5.25	2.61 ± 3.48	3.40 ± 3.57	0.75 ± 1.47	2.60 ± 3.13
	1982	1.72 ± 1.16	3.23 ± 3.27	1.91 ± 1.45	2.41 ± 1.41	0.88 ± 0.76	0.95 ± 1.21	0.31 ± 0.68	0.45 ± 0.53
Onisimus litoralis	1981	-	-	0.83 ± 1.21	4.85 ± 4.72	0.42 ± 0.77	0.56 ± 0.69	0.33 ± 0.94	0.13 ± 0.32
	1982	0.20 ± 0.28	0.13 ± 0.13	0.03 ± 0.09	0.02 ± 0.06	0.09 ± 0.16	0	0.02 ± 0.06	0
Onisimus glacialis	1981	-	-	0.16 ± 0.30	0.60 ± 0.43	0.09 ± 0.16	0.17 ± 0.16	0.14 ± 0.29	0.43 ± 0.66
	1982	0.02 ± 0.06	0.14 ± 0.22	0.02 ± 0.06	0.13 ± 0.20	0.23 ± 0.30	1.11 ± 0.86	0.02 ± 0.06	0.02 ± 0.06
Onisimus juveniles	1981	-	-	0	0.83 ± 0.90	0.05 ± 0.14	0.10 ± 0.17	0	0.08 ± 0.12
	1982	3.44 ± 4.16	11.48 ± 11.32	0.81 ± 1.39	2.64 ± 3.04	19.36 ± 19.68	21.98 ± 21.92	1.52 ± 1.99	2.88 ± 3.23
Gammarus setosus	1981	-	-	0.05 ± 0.10	0.08 ± 0.12	0.13 ± 0.20	1.10 ± 1.88	1.61 ± 1.73	4.73 ± 3.08
	1982	0.11 ± 0.22	0.03 ± 0.09	0.03 ± 0.09	0.05 ± 0.10	0.30 ± 0.46	0.22 ± 0.30	0.22 ± 0.29	1.14 ± 0.83
Ischyrocerus sp.	1981	-	-	0.31 ± 0.27	1.63 ± 1.49	3.72 ± 3.18	8.58 ± 10.25	7.09 ± 7.35	13.03 ± 9.90
	1982	0.28 ± 0.30	0.30 ± 0.31	0.48 ± 0.51	0.39 ± 0.34	6.94 ± 4.66	7.97 ± 5.32	3.86 ± 3.34	7.34 ± 7.34
Amphipoda	1981	-	-	2.91 ± 1.94	15.20 ± 11.83	7.28 ± 5.65	14.10 ± 12.19	13.91 ± 11.87	32.45 ± 24.47
	1982	6.20 ± 5.49	16.23 ± 11.69	3.38 ± 2.79	5.83 ± 3.72	28.78 ± 23.96	33.05 ± 26.14	6.30 ± 5.33	12.16 ± 10.03

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Pre-spill (August 1981) and Post-spill (September 1981, August 1982, September 1982).

Appendix C. Biomass (mg/m^2) of dominant amphipods on the under-ice surface in four bays[1] at Cape Hatt, Baffin Island, during May 1981 and 1982[2]. Data are based on 10-16 samples, each covering 4 m^2, in each bay and sampling period.

Taxon	Year	Bay 7 Early May mean ± SD	Bay 7 Late May mean ± SD	Bay 9 Early May mean ± SD	Bay 9 Late May mean ± SD	Bay 10 Early May mean ± SD	Bay 10 Late May mean ± SD	Bay 11 Early May mean ± SD	Bay 11 Late May mean ± SD
Weyprechtia pinguis	1981	-	-	46.4 ± 41.7	103.0 ± 73.9	88.5 ± 124.6	29.5 ± 27.8	14.2 ± 26.0	7.7 ± 13.7
	1982	58.2 ± 58.1	45.1 ± 35.8	74.5 ± 66.0	64.5 ± 55.4	21.6 ± 20.5	24.2 ± 41.1	11.0 ± 27.9	5.0 ± 10.5
Onisimus litoralis	1981	-	-	31.1 ± 45.9	219.7 ± 222.5	13.3 ± 26.4	25.4 ± 32.9	14.1 ± 43.8	3.9 ± 9.6
	1982	14.4 ± 22.8	8.9 ± 10.0	2.7 ± 7.4	1.6 ± 6.4	6.8 ± 11.9	0	1.4 ± 5.6	0
Onisimus glacialis	1981	-	-	1.9 ± 3.6	8.2 ± 5.0	1.1 ± 2.2	3.0 ± 3.2	1.2 ± 2.4	4.2 ± 7.0
	1982	0.2 ± 0.6	1.1 ± 1.9	0.2 ± 0.8	1.0 ± 1.6	2.5 ± 3.6	6.2 ± 5.9	0.1 ± 0.4	0.2 ± 0.8
Onisimus juveniles	1981	-	-	0	3.3 ± 3.8	0.1 ± 0.3	0.6 ± 0.9	0	0.3 ± 0.6
	1982	6.2 ± 7.6	26.4 ± 25.5	1.5 ± 2.5	6.0 ± 6.9	36.2 ± 37.6	58.3 ± 56.8	2.5 ± 3.0	5.7 ± 6.3
Gammarus setosus	1981	-	-	0.3 ± 0.6	0.8 ± 1.6	0.6 ± 1.1	5.9 ± 8.5	66.7 ± 69.7	206.6 ± 168.9
	1982	1.8 ± 4.6	0.8 ± 2.9	0.1 ± 0.3	0.3 ± 0.7	1.9 ± 3.3	3.8 ± 7.6	33.0 ± 42.6	184.8 ± 146.2
Ischyrocerus sp.	1981	-	-	0.6 ± 0.8	5.1 ± 4.2	9.8 ± 7.7	27.5 ± 36.7	10.2 ± 12.6	22.0 ± 18.6
	1982	0.4 ± 0.5	0.6 ± 0.6	0.8 ± 0.7	0.7 ± 0.6	11.9 ± 8.8	20.0 ± 14.7	3.6 ± 3.5	11.8 ± 14.6
Amphipoda	1981	-	-	82.3 ± 69.0	353.5 ± 265.3	117.6 ± 125.8	93.5 ± 73.8	111.4 ± 133.9	264.3 ± 211.2
	1982	81.8 ± 70.7	86.9 ± 37.6	80.0 ± 68.3	74.3 ± 55.9	90.0 ± 53.6	129.5 ± 97.5	68.3 ± 62.3	215.7 ± 150.9

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Pre-spill (August 1981) and Post-spill (September 1981, August 1982, September 1982).

Appendix D. Density (nos./m^2) of dominant amphipods and tide levels (cm below mean) in the intertidal habitats of four bays[1] at Cape Hatt, Baffin Island, during August and September 1981 and 1982[2]. Data are based on 10 samples, each covering 0.25 m^2, in each bay and sampling period.

Taxon	Year	Bay 7		Bay 9		Bay 10		Bay 11	
		August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD
Gammarus setosus	1981	-	0	42.0 ± 21.6	23.6 ± 34.1	102.4 ± 129.4	85.2 ± 61.4	95.2 ± 58.9	12.8 ± 20.6
	1982	355.2 ± 310.2	501.6 ± 342.5	758.8 ± 316.1	649.2 ± 430.2	398.4 ± 399.0	376.0 ± 322.7	138.8 ± 157.1	222.4 ± 278.6
Onisimus litoralis	1981	-	0	0	0	0.8 ± 1.7	0.4 ± 1.3	12.8 ± 7.3	0.8 ± 1.7
	1982	2.8 ± 3.3	5.2 ± 5.0	34.0 ± 19.3	376.4 ± 745.8	78.4 ± 103.3	572.4 ± 952.8	216.0 ± 136.6	473.2 ± 501.3
Onisimus glacialis	1981	-	0	0	0	0	0	0	0
	1982	2.8 ± 3.8	2.4 ± 3.4	63.6 ± 60.3	228.0 ± 637.8	236.4 ± 224.3	237.6 ± 377.3	633.6 ± 245.0	398.0 ± 476.1
Monoculodes packardi	1981	-	0	0	0	0	0	0	0
	1982	0.8 ± 1.7	0	31.2 ± 25.5	165.6 ± 277.0	81.6 ± 159.5	287.6 ± 414.9	10.4 ± 22.4	2.0 ± 3.9
Amphipoda	1981	-	0	43.2 ± 29.0	23.6 ± 34.1	108.0 ± 135.0	86.4 ± 60.6	111.6 ± 67.5	16.8 ± 21.7
	1982	362.4 ± 315.7	511.2 ± 346.3	892.8 ± 310.2	1,468.8 ± 1,375.7	805.2 ± 541.7	1,514.8 ± 1,345.8	1,065.6 ± 399.5	1,146.4 ± 892.2
Tide levels (cm below mean)	1981	-	28-31	36-49	33-34	101-103	33-34	57-64	26-31
	1982	66-75	68-78	74-87	68-87	68-95	68-93	89-101	71-94

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Pre-spill (August 1981) and Post-spill (September 1981, August 1982, September 1982).

Appendix E. Biomass (mg/m^2) of dominant amphipods in the intertidal habitats of four bays[1] at Cape Hatt, Baffin Island, during August and September 1981 and 1982[2]. Data are based on 10 samples, each covering 0.25 m^2, in each bay and sampling period.

		Bay 7		Bay 9		Bay 10		Bay 11	
Taxon	Year	August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD	August mean ± SD	September mean ± SD
Gammarus setosus	1981	-	0	1,132 ± 799	223 ± 242	621 ± 718	1,246 ± 1,072	1,070 ± 1,171	521 ± 635
	1982	8,325 ± 8,198	13,891 ± 9,692	13,522 ± 7,343	17,175 ± 9,417	4,993 ± 4,845	6,672 ± 7,073	2,103 ± 1,739	2,320 ± 2,582
Onisimus litoralis	1981	-	0	0	0	52 ± 123	32 ± 100	770 ± 440	60 ± 126
	1982	22 ± 26	52 ± 50	304 ± 168	4,335 ± 8,809	676 ± 837	6,423 ± 10,541	1,793 ± 1,243	5,313 ± 6,009
Onisimus glacialis	1981	-	0	0	0	0	0	0	0
	1982	22 ± 31	23 ± 33	454 ± 424	1,993 ± 5,538	1,664 ± 1,651	2,301 ± 3,778	4,271 ± 1,800	3,304 ± 4,193
Monoculodes packardi	1981	-	0	0	0	0	0	0	0
	1982	1 ± 2	0	12 ± 9	93 ± 153	27 ± 50	144 ± 209	3 ± 5	1 ± 2
Amphipoda	1981	-	0	1,353 ± 846	223 ± 242	1,202 ± 1,400	1,292 ± 1,056	1,850 ± 1,423	842 ± 796
	1982	8,371 ± 8,230	13,973 ± 9,757	14,312 ± 7,215	23,837 ± 13,311	7,471 ± 4,257	16,064 ± 13,786	8,740 ± 3,999	11,551 ± 9,301

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[1] Bay 7 (reference), Bay 9 (dispersed oil release), Bay 10 (dispersed oil contamination), Bay 11 (surface oil release).

[2] Pre-spill (August 1981) and Post-spill (September 1981, August 1982, September 1982).

Appendix F. Density (nos./m^2 x 10^3) of major meiofaunal groups exposed to oil^1 and chemically treated oil^1 in two locations on the under-ice surface at Cape Hatt, Baffin Island, during 18 May-2 June 1982. Data are expressed as mean ± SD and based on 4 replicate ice cores (10 cm diameter) for each treatment, location and sampling period.

			Treatment					
Taxon	Period^2	Location	Control	Oil^1	Solidified Oil^1	BP CTD +Oil^1	BP 1100WD +Oil^1	Corexit 9527 +Oil^1
Copepoda	Pre-spill 1	1	54.51 ± 12.90	7.08 ± 6.22	26.97 ± 10.14	51.64 ± 13.58	36.15 ± 27.67	36.72 ± 25.75
		2	52.40 ± 13.69	54.89 ± 11.64	86.19 ± 11.53	30.41 ± 5.35	13.39 ± 10.39	68.95 ± 19.81
	Pre-spill 2	1	65.63 ± 21.37	13.85 ± 12.42	39.82 ± 14.24	58.90 ± 39.34	62.98 ± 20.51	45.76 ± 16.57
		2	79.69 ± 20.43	60.80 ± 11.73	76.35 ± 6.32	26.78 ± 14.22	30.90 ± 22.36	90.28 ± 13.03
	Post-spill 1	1	52.14 ± 13.20	5.41 ± 2.75	22.33 ± 7.60	3.10 ± 1.53	1.87 ± 1.48	2.55 ± 1.55
		2	73.31 ± 12.37	51.53 ± 7.69	46.41 ± 13.69	2.01 ± 2.55	2.69 ± 1.52	2.08 ± 1.65
	Post-spill 2	1	45.15 ± 13.89	7.05 ± 2.89	21.81 ± 7.77	4.70 ± 3.06	3.92 ± 1.37	3.26 ± 2.08
		2	66.77 ± 18.48	41.61 ± 12.23	39.55 ± 7.54	3.01 ± 0.87	2.75 ± 1.78	2.49 ± 1.47
	Post-spill 3	1	36.80 ± 6.97	6.69 ± 2.31	22.14 ± 4.47	5.69 ± 1.62	6.26 ± 3.92	5.00 ± 1.33
		2	57.48 ± 9.80	32.81 ± 8.30	26.46 ± 5.00	10.31 ± 0.84	3.10 ± 2.86	6.87 ± 2.51
Nematoda	Pre-spill 1	1	2.30 ± 1.93	0.57 ± 0.81	0.38 ± 0.54	0.89 ± 0.80	1.05 ± 0.96	1.24 ± 0.85
		2	1.53 ± 1.33	1.24 ± 1.01	0.64 ± 0.44	1.05 ± 0.96	0.10 ± 0.19	2.01 ± 1.96
	Pre-spill 2	1	1.67 ± 1.14	0.18 ± 0.77	0.78 ± 0.18	3.43 ± 1.55	2.63 ± 0.87	0.97 ± 0.23
		2	3.05 ± 1.98	2.66 ± 1.35	0.76 ± 0.30	1.23 ± 0.39	0.42 ± 0.43	1.26 ± 0.70
	Post-spill 1	1	3.33 ± 1.19	0.62 ± 0.20	1.77 ± 1.40	5.99 ± 1.73	4.82 ± 2.71	4.68 ± 2.00
		2	3.55 ± 1.13	4.54 ± 1.65	0.96 ± 0.19	3.95 ± 2.25	0.55 ± 0.49	3.71 ± 1.40
	Post-spill 2	1	4.35 ± 3.55	4.50 ± 1.82	3.20 ± 0.76	18.60 ± 12.22	6.30 ± 3.26	10.35 ± 5.31
		2	4.48 ± 2.01	4.25 ± 4.04	1.57 ± 1.72	4.95 ± 2.88	0.35 ± 0.32	6.64 ± 6.10
	Post-spill 3	1	4.96 ± 2.33	5.24 ± 2.56	2.04 ± 0.51	8.57 ± 3.11	6.90 ± 3.35	7.21 ± 2.38
		2	4.90 ± 2.57	3.27 ± 1.47	3.52 ± 2.41	3.72 ± 1.60	2.96 ± 1.02	5.37 ± 1.30
Polychaeta	Pre-spill 1	1	2.30 ± 1.93	0 ± 0	0.57 ± 0.49	1.15 ± 1.38	0.67 ± 0.65	0.57 ± 0.49
		2	0.89 ± 0.44	3.35 ± 1.18	0.51 ± 0.44	1.34 ± 0.73	0.77 ± 0.94	1.34 ± 1.19
	Pre-spill 2	1	1.48 ± 1.99	1.18 ± 0.63	1.82 ± 0.19	2.13 ± 1.73	1.84 ± 1.37	0.86 ± 0.43
		2	1.25 ± 0.54	3.10 ± 0.51	2.87 ± 0.77	2.56 ± 0.66	1.55 ± 0.74	2.11 ± 0.97
	Post-spill 1	1	1.68 ± 1.51	1.13 ± 1.14	1.98 ± 1.52	0 ± 0	0 ± 0	0.16 ± 0.19
		2	2.83 ± 1.51	2.95 ± 1.11	3.61 ± 0.53	0.13 ± 0.22	0.17 ± 0.34	0.29 ± 0.37
	Post-spill 2	1	1.68 ± 0.89	0.57 ± 0.27	2.28 ± 0.66	0.10 ± 0.17	0.14 ± 0.20	0 ± 0
		2	2.98 ± 0.30	4.25 ± 4.04	2.99 ± 2.78	0.10 ± 0.09	0.08 ± 0.09	0.11 ± 0.08
	Post-spill 3	1	1.68 ± 0.98	1.13 ± 1.07	1.99 ± 0.59	0.15 ± 0.26	0 ± 0	0.22 ± 0.44
		2	1.72 ± 0.39	1.80 ± 0.56	2.71 ± 0.41	0 ± 0	0.26 ± 0.24	0.13 ± 0.26

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[1] Unweathered Lagomedio crude oil.

[2] Oil treatments were applied on 23 and 24 May 1982.

Appendix G. Numbers of dominant[1] copepod groups or species collected on the under-ice surface in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[2]. Data are total numbers in subsamples of 4 replicate ice cores (10 cm diameter) for each treatment and sampling period.

		Treatment					
Taxon	Period[2]	Control	Oil[3]	Soldified Oil[3]	BPCTD +Oil[3]	BP 1100WD +Oil[3]	Corexit 9527 +Oil[3]
Cyclopina schneideri	Pre-spill 1	62	37	50	35	52	78
	Pre-spill 2	460	220	288	292	290	525
	Post-spill 1	356	106	122	1	4	5
	Post-spill 2	580	238	269	22	34	27
	Post-spill 3	261	66	58	40	37	35
Cyclopoid copepodite[4]	Pre-spill 1	359	218	293	176	292	360
	Pre-spill 2	695	696	1,019	564	884	1,099
	Post-spill 1	208	111	88	1	2	7
	Post-spill 2	289	257	326	10	27	23
	Post-spill 3	97	60	94	18	15	17
Tisbe furcata	Pre-spill 1	86	56	18	48	25	100
	Pre-spill 2	206	146	56	89	114	288
	Post-spill 1	144	83	35	5	2	4
	Post-spill 2	182	148	109	11	9	25
	Post-spill 3	97	41	78	11	17	11
Tisbe copepodite	Pre-spill 1	19	1	2	14	8	7
	Pre-spill 2	19	12	15	32	7	32
	Post-spill 1	20	6	10	6	0	2
	Post-spill 2	19	8	43	22	2	3
	Post-spill 3	20	2	14	3	0	1
Nauplii (Cyclopoid and Harpacticoid)	Pre-spill 1	15	14	8	18	21	14
	Pre-spill 2	67	67	48	67	43	80
	Post-spill 1	45	30	24	15	9	5
	Post-spill 2	62	71	109	6	14	16
	Post-spill 3	22	17	20	4	2	3

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[1] 96.6% of total copepod numbers.
[2] Oil treatments were applied on 23 and 24 May 1982.
[3] Unweathered Lagomedio crude oil.
[4] Majority identified is *Cyclopina* sp.

Appendix H. Under-ice productivity and biomass data for variables measured in only three sampling periods at Cape Hatt, Baffin Island, during 18 May-2 June 1982[1]. Sample sizes are given in Appendix A.

Variable	Period[1]	Location	Treatment					
			Control	Oil[2]	Solidified Oil[2]	BP CTD +Oil[2]	BP 1100WD +Oil[2]	Corexit 9527 +Oil[2]
Productivity[3] ($mgC/m^2/h$)	Pre-spill 1	1	1.49 ± 0.13	0.03	0.19 ± 0.01	2.97 ± 0.45	1.12 ± 0.22	0.34 ± 0.07
		2	1.66 ± 1.03	0.96 ± 0.31	0.40 ± 0.19	0.11 ± 0.03	0.11 ± 0.08	3.61 ± 1.25
	Post-spill 1	1	1.92 ± 0.75	0.12 ± 0.03	1.33 ± 0.60	1.15 ± 0.43	1.25 ± 0.14	1.12 ± 0.46
		2	2.45 ± 0.49	1.99 ± 0.27	1.62 ± 0.44	1.26 ± 0.28	0.09 ± 0.08	1.07 ± 0.31
	Post-spill 3	1	2.20 ± 0.05	0.41 ± 0.05	1.57 ± 0.40	2.02 ± 0.35	1.43 ± 0.22	1.40 ± 0.16
		2	2.51 ± 0.58	1.89 ± 0.07	1.14 ± 0.20	1.41 ± 0.32	0.07 ± 0.03	2.05 ± 0.36
Chlorophyll *a*[3] (mg/m^2)	Pre-spill 1	1	10.61 ± 1.66	3.32 ± 0.50	6.30 ± 0.65	11.77 ± 2.40	10.79 ± 1.19	8.02 ± 2.76
		2	12.18 ± 2.02	10.88 ± 0.81	10.50 ± 2.89	6.49 ± 3.50	5.12 ± 0.57	13.05 ± 2.88
	Post-spill 1	1	14.52 ± 1.09	5.68 ± 1.18	14.85 ± 3.18	13.17 ± 1.56	13.72 ± 1.02	11.12 ± 1.39
		2	13.08 ± 1.33	13.07 ± 1.82	12.42 ± 1.06	9.27 ± 1.09	4.13 ± 3.12	11.92 ± 1.08
	Post-spill 3	1	15.20 ± 1.69	9.98 ± 1.17	19.84 ± 3.54	10.82 ± 0.80	12.25 ± 2.81	11.55 ± 2.59
		2	14.70 ± 2.93	13.89 ± 1.46	15.06 ± 3.73	9.57 ± 2.02	6.57 ± 2.73	12.24 ± 3.73
Particulate Carbon[4] (mg/m^2)	Pre-spill 1	1	197.45 ± 1.84	36.87	120.72 ± 26.61	217.72	166.31 ± 6.71	146.12 ± 44.36
		2	-	-	-	-	-	-
	Post-spill 1	1	290.55 ± 34.19	115.74 ± 27.59	214.43 ± 48.36	226.75 ± 26.61	314.11 ± 111.00	208.69 ± 51.06
		2	485.78 ± 26.83	354.81 ± 14.71	356.95 ± 62.32	-	177.71 ± 87.96	264.00 ± 16.34
	Post-spill 3	1	418.53 ± 19.37	225.98 ± 11.04	371.33 ± 46.30	357.87 ± 54.09	298.73 ± 47.28	328.57 ± 30.40
		2	599.99 ± 7.25	355.42	392.67 ±167.15	255.43 ± 69.35	123.47 ± 2.16	367.35 ± 22.29
Particulate Carbon[3] (mg/m^2)	Pre-spill 1	1	426.11 ±196.25	64.57	159.12 ± 56.69	284.27	363.15 ± 115.87	191.17 ± 59.61
		2	-	-	-	-	-	-
	Post-spill 1	1	324.21 ± 49.55	113.45 ± 15.90	262.40 ± 41.11	260.18 ± 17.42	278.08 ± 4.00	200.43 ± 25.53
		2	466.19 ± 36.35	340.96 ± 41.44	337.75 ± 10.49	230.72 ± 27.91	134.56 ± 95.10	405.68 ± 57.23
	Post-spill 3	1	437.27 ± 35.27	182.84 ± 8.66	289.25 ± 20.45	306.92 ± 15.80	246.25 ± 3.79	229.96 ± 28.99
		2	441.41 ± 62.10	313.34 ± 9.95	261.32 ± 64.70	204.33 ± 30.40	84.61 ± 17.96	297.81 ± 7.25
Dissolved Organic Carbon[4] ($mgC/m^2/h$)	Pre-spill 1	1	8.88 ± 0.54	0.20	0.70 ± 0.24	7.68 ± 1.59	4.02 ± 1.72	1.62 ± 0.13
		2	4.41 ± 1.89	2.15 ± 0.77	0.61 ± 0.13	0.35 ± 0.09	0.50 ± 0.30	6.17 ± 1.45
	Post-spill 1	1	9.87 ± 4.39	0.51 ± 0.23	3.57 ± 2.47	4.74 ± 1.14	5.60 ± 0.23	5.03 ± 1.50
		2	11.64 ± 3.36	8.42 ± 1.45	5.84 ± 1.67	3.77 ± 1.01	0.22 ± 0.37	4.46 ± 2.14
	Post-spill 3	1	9.24 ± 0.73	1.86 ± 0.81	6.79 ± 0.78	7.09 ± 1.38	6.54 ± 1.89	5.71 ± 1.06
		2	10.60 ± 1.94	-	-	4.40	-0.04 ± 0.23	5.94 ± 0.47

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[1] Oil treatments were applied on 23 and 24 May 1982.
[2] Unweathered Lagomedio crude oil.
[3] 3.0 μm filter.
[4] 0.45 μm filter.

Appendix I. ^{14}C activity in under-ice copepods exposed to oil[1] and chemically treated oil[1] on the under-ice surface in the productivity study site at Cape Hatt, Baffin Island, during 18 May-2 June 1982[2]. Sample sizes are given in Appendix A.

Variable	Period	Location	Treatment					
			Control	Oil[1]	Solidified Oil[1]	BP CTD +Oil[1]	BP 1100WD +Oil[1]	Corexit 9527 +Oil[1]
^{14}C activity per copepod ($mgC/cop/h \times 10^{-7}$)	Pre-spill 1	1	2.9 ± 0.8	0.2	0.6 ± 0.2	3.9 ± 1.3	1.9 ± 0.8	0.8 ± 0.2
		2	1.8 ± 1.2	3.1 ± 0.9	1.9 ± 0.8	0.5 ± 0.3	0.3 ± 0.1	10.1 ± 2.8
	Post-spill 1	1	4.4 ± 2.1	0.2 ± 2.1	4.1 ± 2.4	2.3 ± 0.3	5.9 ± 3.3	6. 6
		2	5.0 ± 1.6	5.7 ± 0.1	4.5 ± 0.9	7.5 ± 3.2	0.8 ± 0.6	1.5 ± 0.8
	Post-spill 3	1	6.0 ± 0.6	2.9 ± 2.2	3.4 ± 0.7	6.1 ± 1.8	2.9 ± 0.1	5.4 ± 2.7
		2	4.4	6.0 ± 0.7	3.5 ± 1.1	6.2 ± 1.0	-0.2 ± 0.6	7.0 ± 0.9
Copepod secondary productivity ($mgC/m^2/h \times 10^{-3}$)	Pre-spill 1	1	13.6 ± 3.0	0.0	1.2 ± 0.3	19.0 ± 0.9	7.6 ± 7.2	2.1 ± 1.6
		2	8.1 ± 2.7	18.3 ± 7.4	15.2 ± 5.4	1.5 ± 0.9	0.5 ± 0.3	68.3 ± 42.0
	Post-spill 1	1	23.5 ± 13.2	0.3 ± 0.9	10.1 ± 8.9	0.5 ± 0.0	1.6 ± 1.8	1.1
		2	39.6 ± 15.8	31.3 ± 1.9	21.4 ± 9.2	1.1 ± 1.4	0.2 ± 0.1	0.3 ± 0.4
	Post-spill 3	1	24.3 ± 5.2	1.8 ± 0.8	7.8 ± 2.8	3.6 ± 1.8	1.5 ± 1.1	2.4 ± 0.8
		2	27.2	22.3 ± 6.7	7.6 ± 1.2	6.4 ± 1.4	0.1 ± 0.1	4.2 ± 1.9

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[1] Unweathered Lagomedio crude oil.

[2] Oil treatments were applied on 23 and 24 May 1982.

PART II

BEHAVIOUR OF SUBSURFACE DISCHARGES OF OIL, GAS AND DISPERSANTS

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A report prepared for the Baffin Island Oil Spill Project

ABSTRACT

This report contains descriptions of a number of research studies which culminated in the design of the discharge system for the dispersed oil spill in the Baffin Island Oil Spill Program (BIOS). Experimental data are reported on the oil droplet sizes resulting from laboratory discharges of

(i) oil alone
(ii) oil and gas mixtures
(iii) oil and dispersant mixtures
(iv) oil, water and dispersant mixtures.

The use of dispersants reduces oil droplet diameter from millimetres to approximately 10 μm. Test results used to assist the design of the BIOS dispersed oil discharge are described.

A simple method of estimating the particle size of oil-in-water emulsions is described based on observation of settling times. This method when applied to the BIOS discharge indicates that the oil droplet size produced was 10±5μm. Such drops have negligible buoyant velocity under the BIOS test conditions.

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1.0 INTRODUCTION

This report contains accounts of two sets of experiments which had quite different objectives but which concerned the same physical system, namely the discharge of non-aqueous fluids at relatively high velocity into water.

The first set of experiments were undertaken as an exploratory study of the behaviour of a subsea blowout of crude oil with and without gas present. When control is lost of an exploratory or production well, the high pressure oil and/or gas may flow as a two phase system through the well-bore at high velocity, the gas expanding as the pressure falls. Depending on the velocity and gas to oil volume ratios, several flow regimes may apply such as bubble, slug, transition or annular flow. These two-phase flow characteristics have been the subject of intensive study (for example, Oshinowo and Charles 1974 a,b, Govier and Aziz 1972 and Clark and Perkins 1981). When this fluid mixture jets into the water column at the sea bottom, the oil and gas streams fragment into small drops and bubbles of variable size which rise by natural buoyancy to the surface. The behaviour of this rising plume has also been extensively studied notably by Topham (1975), Ditmars and Cederwall (1974) and Fannelop and Sjoen (1980). A review of the status of technology which can be used to intercept and recover the hydrocarbons from this plume has been published recently by Meikle et al (1980).

An interesting aspect of this issue is that at the high pressures and low temperatures which may apply to blowouts in deep water, the gas may form solid hydrates thus reducing its specific volume and buoyancy characteristics (Bishnoi (1979)).

The entire issue of the behaviour of such releases in cold climates has been reviewed by Milne and Herlinveaux (1976) and many aspects of the problem have been discussed in papers in the Annual Arctic Marine Oilspill Program Technical Seminars (e.g. Environment Canada 1981). For the purposes of this work, it is sufficient to note that it is critically important to understand the range of likely oil and gas particle sizes which will be encountered in a blowout. Small particles will rise more slowly, have greater surface areas and may drift for considerable distances and times before reaching the surface. Indeed, very small oil drops may never surface.

The first work described here was undertaken and reported as a bachelor's thesis project by Nilsson (1980) largely as an exploratory study of how velocity and the pressure of gas altered oil drop size distributions. The work was severely limited by difficulties in particle size measurement due to lack of suitable equipment. In this study, chemical dispersant was added to the oil (purely for interest) and the nature of dispersed oil plumes studied. It was shown that the addition of a small quantity of dispersant caused the oil drop diameter to fall from typically 1 mm to 10 µm resulting in a cloud of slowly rising oil particles which would be similar in characteristics to those formed during chemical dispersion of an oil spill.

This novel method of forming oil in water emulsions was subsequently adopted in modified form by the BIOS project as the method used to generate a defined dispersed oil plume. Further experiments were undertaken using a Coulter Counter for particle size measurement, specifically to obtain design data for the discharge.

A method was also devised for measuring the approximate oil particle size during the BIOS experiment, the method and results being reported here.

A major purpose of the BIOS project was to determine the difference in behaviour and effects of crude oil which impinges on an Arctic shoreline with and without chemical dispersion. An obvious approach is to spill two identical quantities of oil close to shore, disperse one and leave the other untreated, observe the behaviour and make measurements of concentration and the nature of oil in the water column, bottom and shoreline with complementary biological/ecological studies. In practice, this idealized system is not easily and reliably accomplished since it may be difficult to disperse the oil effectively without disturbing the site and there is a risk that if dispersion was ineffective, or only partially effective (due, for example, to application problems), the results would be difficult to interpret. **Accordingly,** the approach in the dispersed oil case was to spill oil under artificial conditions such that dispersion is assured and is accomplished in a reliable, predictable manner.

There are two general methods of generating artificially dispersed oil. The first is to mix oil, dispersant and water in an agitated (eg. stirred) vessel then pump the mixture into the water through a pipe. Since it was decided to spill 15 m³ of oil and the dispersion in the tank should have a concentration no greater than 1000 ppm the volume of water processed must be 15000 m³. Since the aim is to create a plume of oil of concentration 10 ppm, this could involve pumping of the order of 1/100th of the volume of the water at the test site. This could result in severe local disruption of the water column since the dispersion can only be pumped into a small fraction of the area. If the residence time of the oil dispersion was 2 minutes in the mixing vessel and the total discharge time was 6 hours, the vessel volume must be 83 m³ or a 4.4 m cube (ie. 15000 m³ x 2 mins/360 mins). The pumping rate would be 42 m³/minute or 9000 Igal /min which is an appreciable flowrate. At a pipe velocity of 5 m/s, a pipe of area 0.14 m² would be required (diameter 42 cm).

A second, simpler and preferred method is to pump premixed oil dispersant and water from shore and discharge it through a series of jets directly into the water column. The jet will break up into a cloud of dispersed oil particles which, it is hoped will be close in particle size distribution to those obtained by application of dispersant to oil on the sea surface. The principal advantage of this system is that it is mechanically simple and involves pumping only 15 m³ of oil which has been premixed with 0.75 m³ of dispersant on shore and a volume of water which need not be stored.

In the first experiments, oil-dispersant mixtures were discharged and in later tests, oil-dispersant-water mixtures were used. The water was included since it was feared that the relatively high viscosity could give rise to pumping difficulties and to excessive pressure drops which would result in uneven discharge from the perforated pipe which was ultimately used at BIOS. Essentially, the inclusion of water renders the entire design more reliable and robust. Ratios of 5:1 to 10:1, water to oil were contemplated.

Exploratory experiments were conducted to determine if the particle size distribution obtained from a jet is similar to that obtained on the surface and to provide a conceptual design for the delivery system. A Coulter-Counter was provided to measure particle size.

It is apparent from these studies that chemical dispersant can have a profound effect on the behaviour of subsea oil discharge thus enabling human intervention to substantially modify oil spill behaviour and thus effects. For example, dispersant could be injected into a subsea oil discharge resulting in a long delay in oil rise to the surface. Dispersant added to a leaking tanker cargo at the point of release would behave similarly. Obviously the full environmental implications of such measures would require assessment but there may be cases in which the use of dispersants in such circumstances is justified. Elimination of fire hazard, at least temporarily, is an example. Finally, the technique of forming dispersions by discharging oil-dispersant mixtures into water may be useful in toxicity studies where defined and controlled particle sizes are necessary.

2.0 EXPERIMENTAL AND RESULTS

2.1 Oil-Gas Dispersant Discharges

The experiments were undertaken in an aluminum column with a rectangular cross section (Figure2.1) containing water and into which gas and oil were introduced through a pipe at the bottom. The column was equipped with three rectangular lucite windows through which the bubbles and drops were observed and photographed. The lucite tank and the outer plastic tubing were constructed to accomodate the currents which may occur along the side-walls downwards in the apparatus.

Oil and gas were introduced into the apparatus through glass **tubes** of 3 mm and 8 mm internal diameter (5 and 10 mm outside diameter). The distance between the outlet of pipe and the water level at the top of the apparatus was 2.15 m. The flowrate of gas was measured by a rotameter and of oil using a glass tube of cross section area 2.5 cm², by measuring the distance which the oil interface moved during a measured time. The oil was forced through the glass tube by compressed air. All parts were connected by Tygon tubing.

When gas alone was introduced, the change of the water level in the tank was measured by a micrometer to estimate the average volume of gas bubbles in the apparatus, but this proved to be difficult since the change was of the order of 1 mm and could not be determined accurately.

The oil and gas experiments were carried out with tap water at a temperature of 20°C as the continuous phase. When dispersants were tested, salt water was used.

Air was used instead of natural gas for convenience and safety.

The first exploratory experiments were carried out with ke-

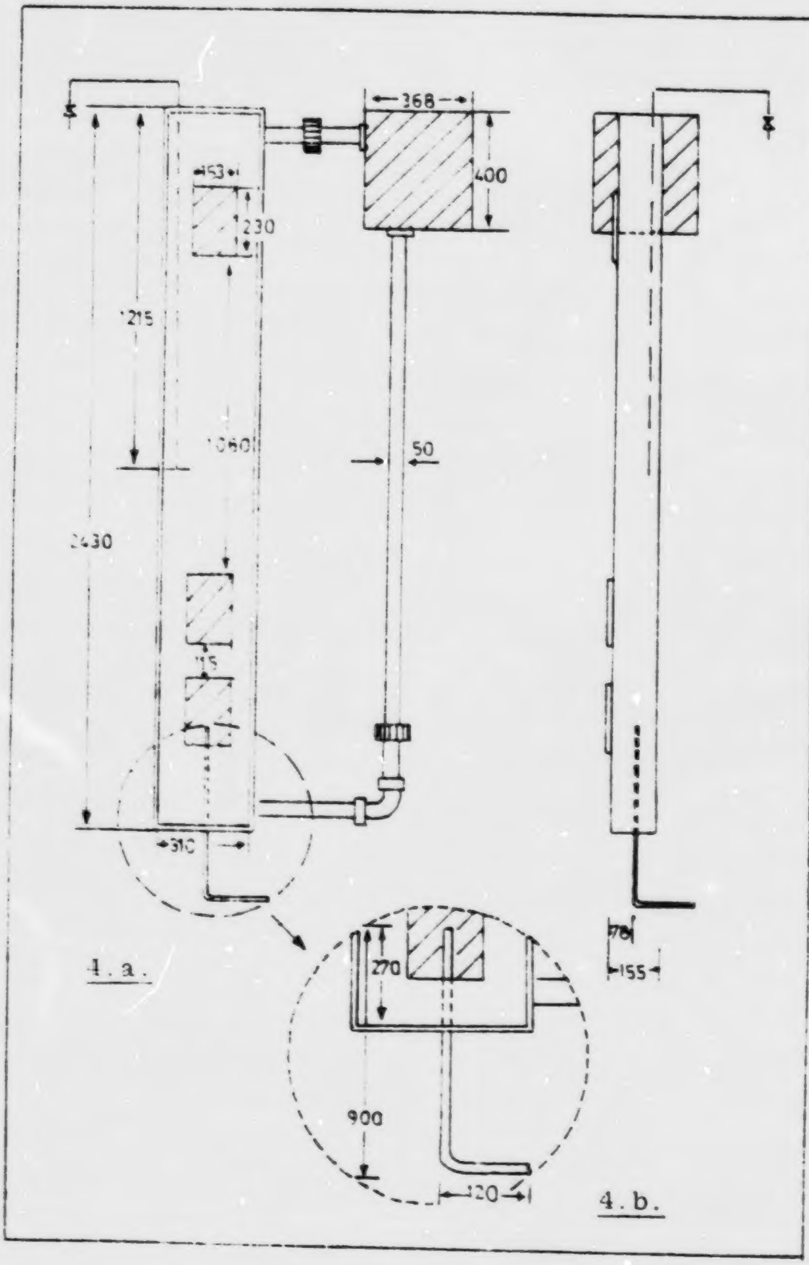

368
400
153
230
1215
1060
2430
50
115
310
4.a.
270
900
120
4.b.
78
155

Figure 2.1 Apparatus.

rosene, coloured by red dye, (Sudan IV Red Dye), instead of oil. Kerosene is less viscous and easier to handle than most crude oil. Photographs were taken with an Olympus OM1 camera with a Vivitar 283 flash unit using 400 ASA film.

The crude oil was Alberta Sour Blend supplied by BP and the dispersant was Corexit 9527, which was premixed with the oil. Properties are given in Table 2.1.

TABLE2.1 PHYSICAL PROPERTIES AT 20^{o} FOR MATERIALS USED IN THE EXPERIMENTS

MATERIALS	DENSITY kg/m^3	VISCOSITY (Pa s)x10^3
Air	1.29	0.018
Water	998	1.06
Kerosene	801	2.00
Alberta Sour Blend	832	9.50
Corexit 9527	1010	0.68

Crude oil-water interfacial tension was 24.1×10^{-3} N/m.

From the pictures, the number and the diameter of the bubbles were measured by a Tektronics particle size analyzer. Histograms showing the number of bubbles in different diameter ranges were prepared by a computer program and histograms showing the volume of bubbles in different diameter ranges were prepared from these diameter histograms by hand.

Drops of diameter less than 100 μm could not be reliably observed, thus an attempt was made to estimate their number and volume by measuring the decrease in oil concentration with time after each experiment. The volume of drops in this diameter range and the amount of oil dissolved in the water can then be calculated from the rising velocities. The oil concentrations were measured by Horiba IR oil content analyzer.

Experiments with gas alone were performed at six different flowrates with two pipe diameters.

Bubble velocities obtained from the picture and the measurements in the upper tank were compared and the results are shown in Table 2.2 below.

TABLE:2.2 AVERAGE RISING VELOCITIES IN m/s FOR AIR BUBBLES: OBTAINED PHOTOGRAPHICALLY FOR THE TWO PIPE DIAMETERS

Air Flow	Pipe Inside Diameter	
cm^3/s	3 mm	8 mm
9.5	0.238	0.238
25.0	0.238	0.241
50.0	0.241	0.253
77.5	0.244	0.259
101.5	0.259	0.259
119.0	0.256	0.256

The velocities did not vary significantly with either air flow or source diameter being about 24 cm/s for a pipe diameter of 3 mm and 25 cm/s for a pipe diameter of 8 mm O.D.

Velocities, corresponding to the bubble diameters obtained from the photographs, from the literature for single bubbles rising in a stagnant fluid are higher than those measured since, in the experiments, the air bubbles were rising as a plume. According to studies of air plumes done by Ditmars et. al. (1974) and Topham (1975), the rising velocity of a bubble in a plume exceeds the rising velocity of a single bubble. Similarity can only exist if the air bubbles are so small that their rising velocity relative to the induced plume is negligible.

The discharge of air bubbles into water creates a turbulent plume of an upward rising mixture of air and water by reducing the bulk density of water. The expansion of the rising air bubbles which causes the driving force for the system, buoyancy, to vary must be taken into consideration. The rising plume also entrains water from the depth until it reaches the surface.

The bubble diameters varied but most of the gas was in bubbles of 5 to 15 mm diameter.

Experiments with kerosene and oil individually were undertaken with two pipe diameters, 3 mm and 8 mm at five different flowrates, the average drop diameters being shown in Table 2.3. The drops are consistently in the 5 to 10 mm diameter range.

TABLE:2.3 AVERAGE DIAMETERS OF KEROSENE AND OIL DROPS FOR THE TWO PIPE DIAMETERS; WHEN INJECTED ALONE

	3 MM DIAMETER		8 MM DIAMETER	
	$m^3/s \times 10^6$	$m \times 10^3$	$m^3/s \times 10^6$	$m \times 10^6$
Kerosene	0.119	5.059	0.139	6.683
	0.229	5.227	0.257	6.718
	0.573	5.695	0.517	7.608
	0.912	4.997	0.848	8.081
	1.289	5.237	1.116	8.026
Oil	0.127	5.770	0.127	7.488
	0.257	6.038	0.271	7.423
	0.532	6.545	0.512	8.753
	0.863	6.628	0.851	9.037
	1.106	6.144	1.097	8.851

Experiments with oil or kerosene mixed with air were undertaken with the two pipe diameters at four flowrates. The volume ratio between the gas and liquid flowrates was approximately 100:1 but at one gas flowrate (12.0 cm³/s), experiments were also carried out with a ratio of approximately 24:1.

The results, when using kerosene or oil and air, are shown in Table 2.4.

When oil and air were injected together, the oil was shattered into droplets within a short distance of the pipe exit, with an average diameter of approximately 1 mm which is similar to the results obtained by Topham (1975). The diameter of the oil drops was thus reduced by 5 to 10 when oil and air were injected together. The higher flow rate produced smaller droplet sizes, as did the larger pipe diameter for the same ratio (100:1) between the air and the oil flowrate. When the ratio decreased (24:1), the diameter of the oil droplets increased.

The experiments with kerosene gave the same results as for oil.

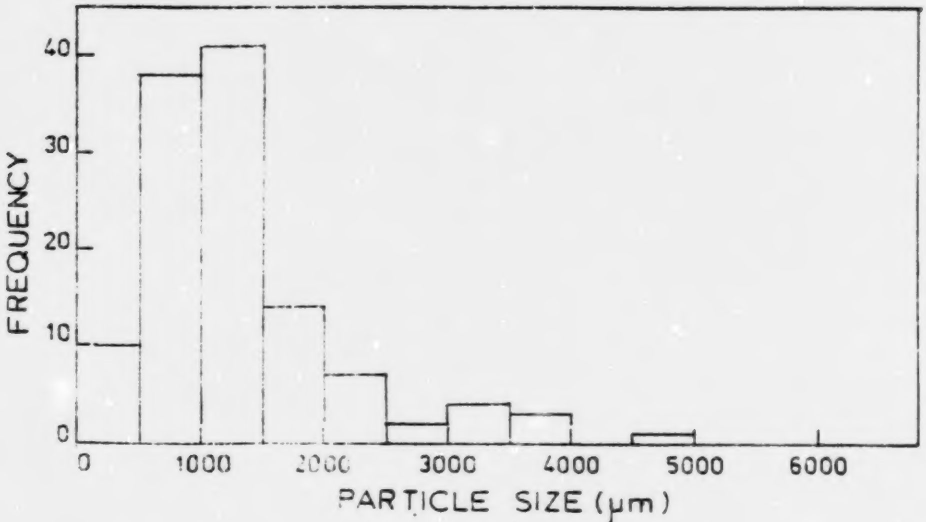
In the average diameters discussed above, the smallest particles (diameters less than 100 μm) were not included. An attempt was made to estimate the distribution of smaller drops by observing the concentration changes on settling. It was apparent that a few percent of the volume of the oil is present as very small (<100 μm) drops.

The size distribution of the oil drops is very important for determining the rising time for the oil drops and of how far they will surface from the blowout. Graphs of the resulting droplet distributions are shown in Figures 2.2to2.4. Each sample consisted of a count of approximately 120 drops total. This sample size is rather small and the graphs should be regarded as indications of dropsizes rather than accurate determinations.

The histograms for different flowrates were similar. Topham (1975) found that there was a more marked difference between flowrates of 60 cm³/s and 450 cm³/s. The reason for this is not known. In the histograms discussed here, the smallest particles (diameters less than

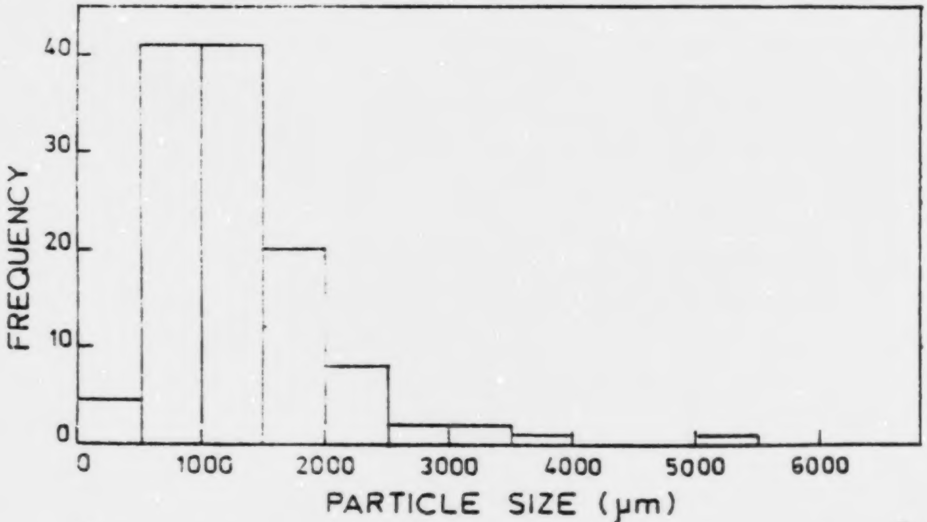
TABLE: 2.4 AVERAGE DIAMETER OF LIQUID DROPS FOR THE TWO PIPE DIAMETERS WHEN KEROSENE OR OIL AND AIR WERE INJECTED TOGETHER

	GAS FLOW $m^3/s \times 10^6$	LIQUID FLOW $m^3/s \times 10^6$	RATIO	DIAMETER $m \times 10^3$	GAS FLOW $m^3/s \times 10^6$	LIQUID FLOW $m^3/s \times 10^6$	RATIO	DIAMETER $m \times 10^3$
	3 MM DIAMETER				8 MM DIAMETER			
Kerosene	12.0	0.530	23	1.089	12.0	0.495	24	1.129
	12.0	0.147	82	0.986	12.0	0.119	101	0.708
	50.0	0.517	97	0.860	50.0	0.495	101	0.762
	90.0	0.888	101	0.894	90.0	0.846	106	1.501
	120.0	1.086	110	0.761	120.0	1.069	112	1.043
Oil	12.0	0.523	23	1.429	12.0	0.509	24	1.723
	12.0	0.127	94	1.200	12.0	0.122	98	1.294
	50.0	0.512	98	1.324	50.0	0.515	97	1.452
	90.0	0.879	102	1.339	90.0	0.871	103	1.254
	120.0	1.126	107	1.068	120.0	1.100	109	1.046



Air flowrate : 90 cm^3/s Oil flowrate : 0.88 cm^3/s

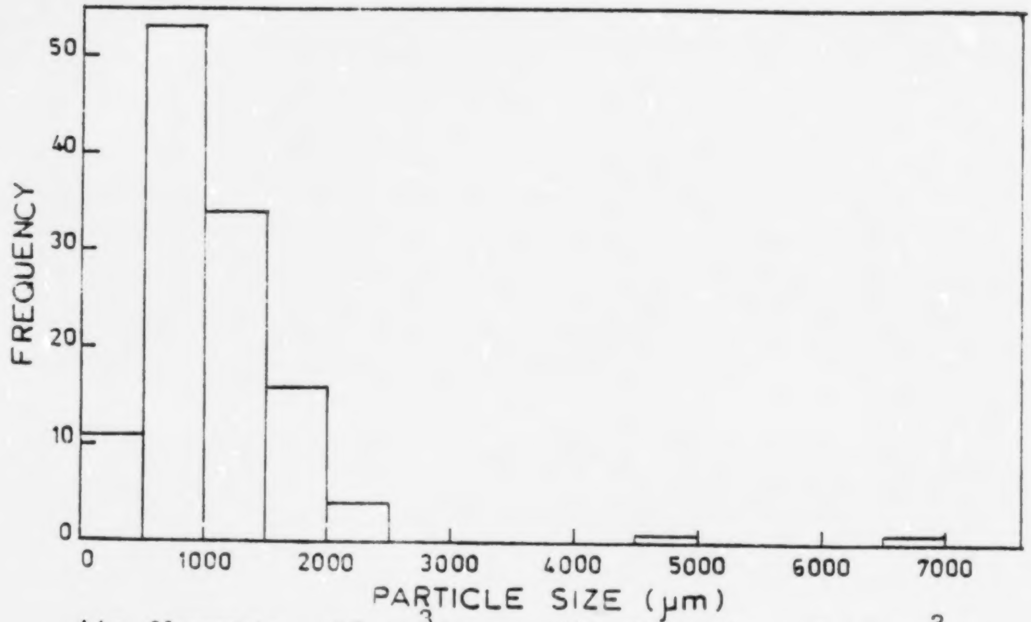
Pipe diameter : 5 mm O.D.



Air flowrate : 90 cm^3/s Oil flowrate : 0.87 cm^3/s

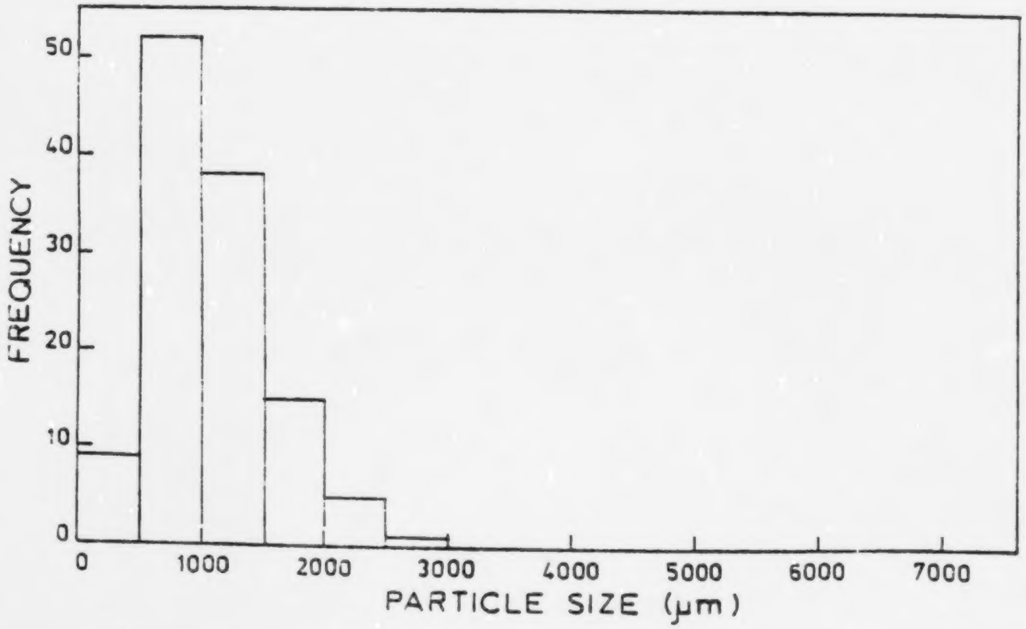
Pipe diameter : 10 mm O.D.

Figure 2.2 Size distribution of oil drops for different pipe diameters.



Air flowrate : 12 cm^3/s Oil flowrate : 0.13 cm^3/s

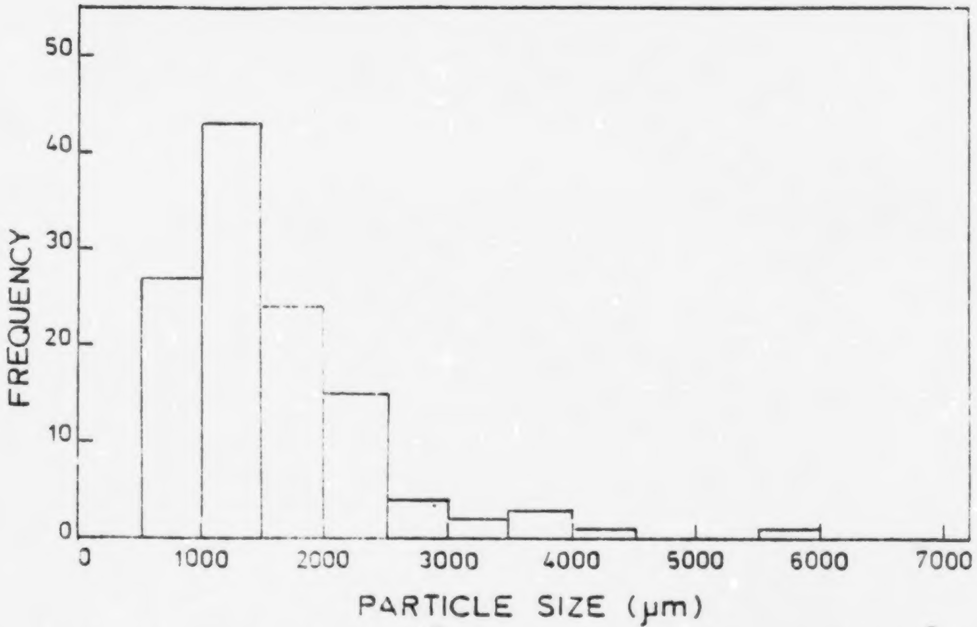
Pipe diameter : 5 mm O.D.



Air flowrate : 120 cm^3/s Oil flowrate : 1.13 cm^3/s

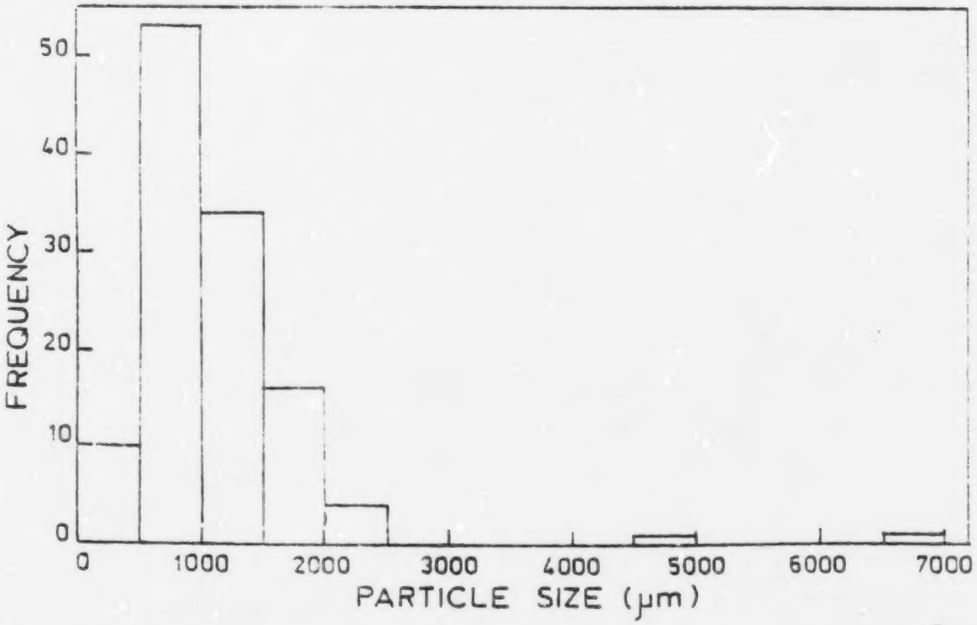
Pipe diameter : 5 mm O.D.

Figure 2.3 Size distribution of oil drops for different volumetric flowrates.



Air flowrate : 12 cm^3/s Oil flowrate : 0.52 cm^3/s

Pipe diameter : 5 mm O.D.



Air flowrate : 12 cm^3/s Oil flowrate : 0.13 cm^3/s

Pipe diameter : 5 mm O.D.

Figure 2.4 Size distribution of oil drops for different flowrate ratios air/oil.

100 μm) were not included.

A small portion, of the order of 3% of the oil injected, forms drops of less than 100 μm diameter and these could be mixed downwards at the outer edges of the plume and from there be carried away with small ocean currents.

Most of these small droplets were within the diameter range 10 μm to 50 μm and the distribution for the two diameters were similar.

A small part of the order of 0.2% of the oil injected dissolved in the water.

The configuration of the oil/gas mixture within the exit pipe was expected to be of some importance in influencing drop size. This flow regime is known to be a function of the superficial oil and gas velocities. The flow conditions used here resulted in different flow regimes for the two pipe diameters. In the 3 mm I.D. case, the flow was expected to be of the annular type and for the flow conditions corresponding to 8 mm I.D., the flow was expected to be of the slug flow pattern. As the use of different pipes results in different flow patterns, it may be necessary to adjust the flow rates to give the same superficial velocities and consequently the same flow pattern if accurate results are to be obtained. In practice, the flow obtained in the experiments was in the slug flow region for both diameters.

The experiments with dispersant were carried out with the smaller pipe (3 mm I.D.) at four different flowrates. The ratio between the gas and the liquid flowrates was approximately 100:1 and at one gas flowrate, 12.0 cm^3/s, experiments were also carried out with a ratio of approximately 25:1.

Both oil and kerosene were used and the dispersant was mixed with the liquid before it was injected. The volume ratio of oil to dispersant was 30:1.

The volume of the mixture was 430 cm^3 when the mixture was used individually and 640 cm^3 when the mixture and air was injected together.

It was very difficult to observe any particles by eye since the dispersant scattered the liquid drops to very small particles and it is believed that the oil droplets were in the diameter ranges less than 100 μm. After some time, the oil plume spread throughout the whole apparatus turning the water opaque and it was impossible to see any flow through the windows. This may indicate that for a real oil blowout, the oil would have been spread over a larger volume than when dispersant is absent.

When oil with dispersant and air were injected together, there were apparently more particles in the lower diameter ranges than when oil with dispersant was introduced alone since the oil settled more slowly.

It is apparent that when oil is injected into water at moderate velocities, the drop size is of the order of 5 mm and is controlled largely by surface tension considerations. When gas is injected simultaneously, the drop size falls to of the order of 1 mm probably because (i) the kinetic energy is higher thus the energy available for new surface formation is larger and (ii) the oil leaves the jet as small particles or slugs separated by gas bubbles. When dispersant is added thus reducing the oil-water interfacial tension from approximately 24×10^{-3}N/m (or 24 dyne/cm) by a factor of probably 50 to 500 the oil shatters into very small drops varying below 100 μm. It would be satisfying to propose a correlation between diameter and velocity, Reynolds No. and interfacial tension but this is presently impossible since the latter are not known for the cases in which dispersant is present.

2.2 BIOS Oil Dispersant Discharge

2.2.1 Background

The general aim in these experiments was to simulate to the maximum extent conditions as would apply at the BIOS discharge. Further, it is desirable to ensure that the oil drop sizes produced are typical of those which occur following dispersion on a sea surface. These tasks are rendered difficult by a number of conflicting requirements and by lack of some basic information, thus the experiments done were necessarily designed within certain constraints and contain elments of compromise. It is useful to document the bases for defining the nature and conditions of the experiments.

(a) Coalescence at high concentrations

It is believed that high concentrations of dispersed oil particles may coalesce to form larger particles thus giving atypical results. A concentration of approximately 1000 ppm (which is equivalent to one 10 μm oil drop in every drop of water 100 μm in diameter) is regarded as the maximum tolerable which can be stored under mild turbulent conditions. Ideally, the concentrations should be lower since at a 1000 ppm concentration drops are separated by only nine drop diameters of water.

The approach adopted was to tolerate high concentrations only for a short period of time and under turbulent conditions then dilute rapidly to establish concentration of 10 to 30 ppm.

(b) Lack of Oceanic Particle Size Data

To our knowledge, there have been no studies of dispersed oil particle sizes following dispersion of oil at sea. This may be difficult since there is a considerable background of biotic and mineral matter, especially close to the surface.

It was thus necessary to simulate this process in the laboratory using a small scale dispersant effectiveness test system. Two such systems were available, the "Mackay-Nadeau-Steelman" apparatus using 6 litres of water (Mackay & Szeto 1981) and a hoop apparatus using 20 litres of water in which radially inward-moving waves are generated, this latter system having been used in aerial application trials.

(c) Volume Constraints on Oil, Water and Dispersant

The effectiveness sytems use 6 and 20 litres of water. If a concentration of 10 ppm is sought, the oil volumes become 0.06 cm^3 and 0.20 cm^3 which at a thickness of 0.1 mm would cover areas of 6 and 20 cm^2. Administering 0.006 or 0.02 cm^3 of dispersant accurately (to give a 1:10 dispersant to oil ratio) is clearly impractical. The only feasible approach is to premix the oil and dispersant then add this mixture to the water surface in the effectiveness systems. As is discussed later, the addition of 0.06 cm^3 of oil to the Mackay-Nadeau-Steelman system proved to be difficult since this small volume could be swept to the side and smeared onto the vessel walls. After some experimentation, a volume of 1 cm^3 was adopted which gives a concentration of 167 ppm which is recognized as being unsatisfactorily high but is unavoidable.

In the laboratory jet apparatus, the maximum volume of water which can be conveniently handled in a single test is approximately 200 litres (44 I gallons). It should be noted that this requires 6 kg of salt to achieve 30 parts per thousand. If the 10 ppm maximum concentration is used, the oil volume becomes 2 cm^3 per test. It is impossible to discharge this small volume at a rate of 5 to 20 cm^3/s as appears to be necessary if an excessive number of jets is to be avoided. For example, 15 m^3 in 6 hours is 694 cm^3/s. The minimum discharge time is 3 seconds thus the volume of oil discharged must be 15 to 60 cm^3 which in 200 litres of water gives concentrations of 75 to 300 ppm which is in the same range as those obtained in the effectiveness apparatus. Again it is essential to premix the oil and dispersant.

It was thus concluded that the effectiveness sytems should be operated by dropping of the order of 1 cm^3 of premixed oil and dispersant onto the turbulent water surface. In the jet system, a volume of 15 to 60 cm^3 of oil should be discharged in 3 seconds into 200 litres of water. In both cases, concentrations within a factor of two of 150 ppm should be achieved.

(d) Temperature

The ideal test temperature is approximately 0°C but this is not practical in the laboratory especially for the large scale system for which no cooling system exists. It is believed that a temperature below 3°C would be satisfactory.

(e) Coulter Counting

For highly accurate counting, it is necessary to filter the water to remove particles of dust and microorganisms. This is impractical for large volumes of water thus a "background subtraction" method must be used, with some attendant loss in accuracy. Considerable sample dilution was necessary to avoid coincident counting.

As a result of these considerations, a jet system was designed and built and complementary effectiveness tests were done in the Mackay-Nadeau-Steelman and hoop systems.

2.2.2 Experiments

Jet System

The apparatus consisted of the aluminum tank containing two plexiglass windows described in Section 2.1. A second all glass tank was also used. Oil was injected through a bulkhead fitting at the base. Provision was made to permit water recirculation from top to bottom to facilitate mixing. The volume of water used was 150 L of 30 parts per thousand salinity. The temperature was reduced to 1 to 3°C by adding ice and mixing. Temperature rise was reduced by insulating the outer surface with polystyrene slabs. Sampling was from the bottom, middle or top using taps or syphons.

The first oil discharge system was a 50 mL plastic syringe which was driven by an air cylinder activated by compressed air, the flow and pressure of the air being controlled by valves. A quick-opening valve was used to start and stop the air flow. The duration of the discharge was timed manually with a stop watch.

The jets used were glass tubing of internal diameter 3 mm and 5 mm. Samples were taken after discharge and 1 hour later.

Mackay Nadeau Steelman (MNS) Effectiveness Apparatus

This apparatus has been described by Mackay and Szeto (1980) and consists of a 30 cm diameter glass vessel containing 6 L of water which is swirled with a tangential air flow of variable velocity, thus giving a variable turbulence level. It is believed that this system simulates to some extent natural turbulence at the ocean surface.

The system is normally operated by dropping dispersant onto 10 mL of oil held in a containment ring. In the present work the ring was removed and 1.0 mL of premixed oil and dispersant was added to the water surface. Samples were taken after 10 minutes turbulence and 1 hour later after settling.

Hoop Apparatus

This apparatus has been described by Mackay and Hossain (1980). It consists of a plastic vessel 40 cm in diameter containing 20 L of water which is agitated by a hoop vertically oscillating at 360 strokes per minute creating waves which move radially inwards thus tending to collect the oil at the centre. A volume of premixed oil and dispersant was added to the surface and samples taken after 10 minutes agitation and 1 hour later after settling.

Oil-Water Discharge

In these tests, premixed oil and dispersant (volume ratio 10:1) was pumped at 500 to 900 cm^3/min along ¼ inch pipe into a tee junction along with a flow of water of 3000 cm^3/min and the mixture passed through 2 m of ¼ inch pipe before discharging into 204 L of salt water in a glass tank 100 cm high by 47.5 cm square. The plume was photographed and sampled for particle size measurement.

Particle Size Measurement

The oil particle sizes were measured with a Coulter Counter Model TA II which had variable orifices of 100, 200 and 400 μm and gave particle sizes by number and volume distribution. The samples were diluted in an electrolyte solution (300 mL) which was passed through the counter over a period of several minutes. The counting rate was kept low enough to avoid coincident counting errors. All samples had a background which was partly electronic and partly real in nature. To subtract this background identical volume samples were run in sequence with and without oil sample addition, the particle numbers subtracted, then each number was multiplied by the cube of the mean particle diameter for each channel thus giving the volume distribution. These were totalled and normalized to 100% to yield volume distributions. The results were expressed graphically or as the volume median diameter i.e. the diameter above and below which half the volume of particles was distributed. The number median diameter was of course lower and is regarded as a less useful figure. The upper and lower quartile diameters were also estimated.

Materials

The oil used was "aged Lago Medio" crude oil obtained from EPS Halifax, as used in the BIOS experiment.

The dispersant used was Corexit 9527 supplied by Imperial Oil Ltd. Sarnia.

Salt water was made by dissolving commercial salt in Toronto tap water at a concentration of 30 g/L.

2.2.3 Oil-Dispersant Discharge Results

General

When dispersant was mixed with the oil, it became impossible to use visual or photographic methods to estimate particle size. A cloud of coffee-coloured oil-water mixture rose and expanded to fill the entire system. In some tests, air was injected as well and similar results were obtained. Only with the use of a Coulter Counter was any reasonable data obtained.

When recording these data, the most useful format is to give the median and the lower and upper quartile diameters on an oil volume basis. Thus 7/10/18 μm is a statement that 25% of the oil is less than 7 μm, 25% is between 7 and 10 μm, 25% is between 10 and 18 μm and 25% is above 18 μm.

The Coulter Counter results are distorted by two effects. First the orifice size controls the particle size "window" which is observed. Obviously no particles larger than the orifice are observed and particles less than 1 to 3% of the orifice are not detected. A 100 μm orifice was used in most of this work thus a large population of sub μm drops would not be detected nor would a few large drops. Ideally, the sample should be analysed by several orifices but this was beyond the scope of the present project. The results should thus be taken as semi-quantitative and not as precise determinations.

MNS and Hoop Effectiveness Apparatus

The results shown in Table 2.5 indicate that the MNS apparatus gives smaller particle sizes than the Hoop apparatus but the effect is not large. Most oil in both cases is in the 4 to 18 μm range. These particles rise with a velocity such that the rise 20 cm takes 38 to 2 hours thus they are essentially permanently dispersed. A few quite large and visible drops also form of diameter approximately 200 to 500 μm but

TABLE 2.5 RESULTS OF PARTICLE SIZE DISTRIBUTION MEASUREMENTS IN TEST SYSTEMS EXPRESSED AS LOWER QUARTILE, MEDIAN AND UPPER QUARTILE DIAMETERS IN μm

MNS Apparatus (2.5 cm H_2O pressure drop)

t = 0 4/9/11 (i.e. after 10 minutes mixing)

t = 10 min 4/6/10

t = 60 min 4/6/10

Hoop Apparatus

t = 0 7/10/18 (i.e. after 30 min mixing)

t = 60 4/8/12

t = 120 4/8/10

Jet Apparatus

Jet Diameter mm	Flow cm³/s 10	20	30
2	Re = 60 t = 0 3/4/10 t = 60 3/4/18		
3	Re = 40 t = 0 3/5/12 t = 60 3/4/10	Re = 80 t = 0 3/5/12 t = 60 3/5/10	Re = 120 t = 0 4/7/8 t = 60 3/7/8
4	Re = 30 t = 0 9/16/20 t = 60 5/10/16		

they rise rapidly to the surface in a minute or two.

Jet Apparatus (Oil-Dispersant)

Five experiments were undertaken as illustrated in Table 2.5 to investigate the effects of pipe diameter and velocity. The Reynolds Numbers are given and seem to correlate with the particle size, high Reynolds Number tending to give smaller particles. The particle sizes span the range covered by the effectiveness tests thus it appears that similar distributions are obtained in both systems.

Jet Apparatus (Oil-Dispersant-Water)

Similar results were obtained in the two tests which took place with water to oil ratios of 3:1 and 6:1 and total flows of 65 and 58 cm^3/s. The discharge Reynolds Numbers were of the order of 5000 which is much higher than the tests with oil alone. The reasons are the higher velocities and the lower viscosity. The drops are formed however in the pipe at the tee not at the orifice thus the distribution of particle sizes is presumably a function of this mixing process.

The particle size distribution was difficult to estimate but was quantitatively similar to the jet system being estimated to be (2 to 5)/(10 to 15)/(15 to 20). There appeared to be some larger particles present which may have been formed early or late in the pumping when mixing was incomplete.

In the BIOS discharge, the drop size distribution was established similarly in the pipe at comparable Reynolds Numbers thus it was expected that particle sizes in the range of 5 to 20 μm would occur. It is noteworthy that the BIOS pipe is much longer thus some additional large drop breakup may occur.

2.3 Field Particle Size Measurement

2.3.1 Background

It is useful to have a method of estimating the oil particle size distribution during the BIOS oil-dispersant spill. Such an estimate is of potential value in assisting interpretation of the oil plume behavior. The possibility of installing a Coulter Counter at the site was considered but was rejected for reasons of cost, uncertain reliability after transportation and the complication of counting natural particulate matter in the water column. Two surrogate measurements were investigated, photographic recording and a settling test.

The principle of the photographic test was that a small volume of water containing the dispersed oil was spread on a sheet of unexposed film with the assistance of a wetting agent. The film was then exposed to an electronic photographic flash at a convenient distance of approximately 1 m and developed. The oil particles appeared as white spots on the negative and could be counted and, it was hoped, the size of the particles determined. The system worked satisfactorily for larger oil particles, i.e. greater than 50 μm but became less satisfactory for small particles because of a combination of problems associated with scattering of light around the particle and grain size of the film. Unfortunately, the particles of interest which are in the 1 to 10 μm range could not be detected reliably. It is noteworthy that since the wavelength of light is only slightly less than 1 μm this provides an ultimate limit to optical methods.

A settling system was then devised and tested. A glass tube 20 cm long by 1.0 cm internal diameter was filled with the dispersion and both ends sealed with stoppers. The tube was mounted vertically and allowed to settle. Photographs were taken periodically using a Polaroid camera at a distance sufficient to fill the entire frame. A paper background of black horizontal lines was placed behind the tubes.

As the dispersion settled, the lines became visible in sequence until ultimately the tube became almost clear with only a slight haze. The "settling time" is controlled by the oil particle size as determined by the Stokes' Law velocity.

The concentration of oil in the water was approximately 10% by volume but diluted samples gave better resolution. The oil to water volume ratio could be readily determined after settling was complete.

The recommended procedure is thus to take a sample of the oil-dispersant-water mixture of 100 mL. One tube is filled with this mixture. A second tube which has been prefilled to half volume (i.e. to 10 cm) with the same water is then filled. A third tube prefilled to 15 cm is treated similarly. This gives a fourfold dilution. A duplicate set can also be filled. The tubes are then sealed, inverted a few times to mix the contents then stood vertically in front of the background. Polaroid photos are taken at regular time intervals, say at 0, 2, 4, 8, 16, 32, 64, 128, 256, 512 and 1026 minutes.

From these photos, an approximate particle size analysis can be done using Stokes' Law

$U = gD^2 \ (\rho_w - \rho_o)/18\mu$

$g = 9.81 \ m^2/s$

D = particle diameter (m)

$\rho_w \cong 1017 \ kg/m^3$

$\rho_o \cong 850 \ kg/m^3$

$\mu \cong 1$ cP or 10^{-3}Pas

thus

$$U = \frac{9.81 \ (1017 - 850)}{18 \times 10^{-3}} D^2 = 9.1 \times 10^6 \ D^2 \ m/s$$

The time to travel 20 cm is thus 0.2/U seconds. A table of velocities and times can thus be assembled and used to interpret the results as tabulated below.

Oil Particle Diameter D			Rising Velocity U		Time to travel 20 cm		
m	mm	μm	m/s		s	min	hours
10^{-6}	10^{-3}	1	$9.1\text{x}10^{-8}$	0.33mm/h	-	37000	610
$3\text{x}10^{-6}$	$3\text{x}10^{-3}$	3	$8.2\text{x}10^{-7}$	3.0mm/h	-	4070	68
10^{-5}	10^{-2}	10	$9.1\text{x}10^{-6}$	3.3cm/h	22000	366	6.1
$3\text{x}10^{-5}$	$3\text{x}10^{-2}$	30	$8.2\text{x}10^{-5}$	30cm/h	2441	40.7	0.67
10^{-4}	10^{-1}	100	.00091	330cm/h	219	3.7	-
$3\text{x}10^{-4}$	$3\text{x}10^{-1}$	300	.0082	30 m/h	24.4	0.41	-
10^{-3}	1	1000	.091	330 m/h	2.2	-	-

This shows that within 4 minutes, all particles greater than 100 μm will have settled. Within 40 minutes, particles greater than 30 μm will have settled. After 6 hours, particles greater than 10 μm will settle. The growth in length of the oil layer at the surface can be used as an indication of the distribution of particle sizes. For a 10% by volume oil sample, this layer should become 2 cm long but normally the layer contains trapped water and the interface may be indistinct.

The photographic record provides a characterisation of the particle size distribution which can be reproduced in the laboratory, the same sample being subjected to Coulter Counting to obtain a breakdown of particle size. Some difficulty may arise from coalescence, especially for the more concentrated samples, thus the Stokes' Law analysis may not apply. Further, the settling velocity of the particles is influenced by the settling of other particles in the water column, and the bulk water density is in some doubt. The Stokes' Law calculations must thus be taken as indicative of the particle size and not as an accurate determination.

2.3.2 BIOS Discharge Results

The discharge took place on 27 August 1981 over a period of 6 hours 25 minutes. The oil-dispersant flow average 41 L/min and the water flow 200 L/min giving a ratio of 4:9. Samples were taken of the mixture initially but at a time when there was a flow rate reduction,then after 3 and 6 hours. Since these latter two samples were taken from a "dead end", it is possible that they represent oil which had resided for some time in the pipe and had coalesced.

Samples were placed in the tube rack and photographed periodically for 70 hours. From the photographs, the "settling time" in the water was observed and compared with similar data obtained in the laboratory. The "half times" for settling was estimated to be 10±3 hours for the initial set of three replicate tubes, 1, 3 and 5 hours for the 3 hour samples and 2, 2 and 1 hour for the final set. Accordingly, the oil particle sizes are believed to be as follows.

Initial set	10 μm ± 5 μm
3 hour set	10 to 30 μm
6 hour set	20 to 30 μm

It is believed that no more than 5% of the oil was less than 3 μm since settling was essentially complete by 70 hours. The initial set results are regarded as most reliable. A 10 μm oil drop will rise at a rate of approximately 3.3 cm/hour or less than 1 m per day thus during the time of the experiment, vertical buoyant motion is almost completely insignificant compared to horizontal drift. Further, any movement of oil to the bottom or surface will be controlled by eddy diffusion rather than buoyancy.

It is possible that the plume as a whole may be slightly buoyant as a result of thermal effects and the presence of oil but the magnitude is likely to be quite small especially as the bulk of the plume will consist of entrained "local" water which will be drawn into the jet.

It is thus concluded that the overall performance of the system was as expected and a non-buoyant plume of oil particles was generated, most of which were in the 5 to 15 μm range.

3.0 CONCLUSIONS

When oil alone is discharged through an orifice of diameter 5 to 10 mm at flowrates of 0.1 to 1.2 cm^3/s, the drop diameters formed are typically 5 to 10 mm.

When gas is discharged with the oil under these conditions at a volumetric flowrate some 20 to 100 times that of the oil, the oil drop diameter becomes smaller ranging from 1.0 to 1.8 mm.

In both cases, but especially when gas is present, a population of very small i.e. less than 0.1 mm drops is also formed but they are responsible for only a small fraction,possibly 3% of the oil volume.

Higher flowrates result in smaller drops being formed, probably as a result of the greater energy availability.

When oil-dispersant mixtures (volume ratio 20:1) are discharged, drops of the order of 5 to 20 μm are formed. This provided a convenient method of preparing oil-in-water emulsions. Higher Reynold's Numbers result in smaller particle sizes.

When water is discharged simultaneously with the oil dispersant mixture, similar size distributions result, although the distribution is probably established in the mixing section of the pipe. A system of this type was used to provide design data for the BIOS experiment.

A method of estimating oil droplet size in the field has been devised based on observation of settling times in tubes. When applied to the BIOS test conditions, it was concluded that the oil particle size generated was 10 μm ± 5 μm. Such particles have negligible buoyant velocity under the test conditions.

It is believed that this method of preparing emulsions may find application in toxicological studies of dispersed oil and that the principle of injecting dispersant into oil which is being released under environmental blowout or vessel leakage conditions may be desirable under certain circumstances.

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PART III

BEHAVIOURAL RESPONSES OF BENTHIC INVERTEBRATES EXPOSED TO DISPERSED CRUDE OIL

by

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A report prepared for the Baffin Island Oil Spill Project

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ABSTRACT

A series of experiments were carried out with the purpose of defining behavioural responses in three species of benthic invertebrates, *Strongylocentrotus droebachiensis* (STR), *Serripes groenlandicus* (SER) and *Mya truncata* (MYA), when exposed to Lago medio crude oil. The dosing protocol was designed to correlate with the 1981 BIOS experimental spill program but relied on tank exposures using a flow-through seawater system on site at Cape Hatt, N.W.T. Oil was added to test systems as an oil/dispersant 10/1 mix at 0.5 to 500 ppm, as well as regimes similar to the field spills. Exposures were static for 6-hour periods. Samples were taken for hydrocarbon analysis of seawater and tissues. Each experiment was followed to a 7-day clearance period.

MYA responded to the addition of dispersed oil by ostial closure and siphon retraction. At high doses, there was a decrease in the effectiveness of mantle and siphon retraction following mechanical stimulation.

SER also exhibited sensitivity to oil by ostial closure and siphon retraction. Emergence out of the sediment occurred at concentrations greater than 100 ppm. Increased locomotion was observed. High doses resulted in latent responses of shell gaping and foot extrusion. An earlier response was extreme closure of the valves, resulting in breakage at the margins. A loss of stimulus responsiveness occurred at the 500 ppm dose with a decrease in the effectiveness of siphon and foot retraction, as well as shell closure when stimulated by touch.

STR showed a rapid onset of behavioural changes at 5 ppm and greater. These included a loss of adherence to substrate and a loss of decoration with shells and seaweed. Spines became rigid at low doses and drooped at higher doses even after the removal of the oil. Tube feet retraction was common. Narcosis was evident with a loss in spine and tube feet responsiveness to mechanical stimuli. A dose-response relationship was demonstrated. Recovery was good except at the 500 ppm dose.

Limited observations were carried out to assess the effects of the dispersant Corexit, and to differentiate sensitivities of small and large individuals. All three species took up petroleum hydrocarbons at a level which was dose-related. STR continued to load soft tissues with hydrocarbon transferred from the external body surface even during the clearing periods.

The behavioural data are interpreted in the context of individual survival, of potential for hydrocarbon loading, and generally in relation to the BIOS experimental spill data.

INTRODUCTION

The invertebrate biota inhabiting the Arctic seafloor has been shown to be affected by petroleum. Polychaetes, isopods, and amphipods showed a number of negative responses when exposed (Atlas et al., 1978; Percy, 1977). These included an inability to recolonize contaminated sediments, increased respiration, and death. Observations made during the experimental spills of the Baffin Island Oil Spill (BIOS) project demonstrated that bivalves and urchins were affected, showing emergence out of the sediment and apparent narcosis (Cross and Thomson, 1982).

There is little doubt that acute exposures can have a significant effect on benthic biota. Depending on the location, this may have direct effects on other components of the ecosystem. If the benthic population becomes reduced in feeding areas for marine mammals such as walrus (*Odobenus marinus*) or for seabirds such as eiders (*Somateria* spp.), the results may be locally significant.

The 1981 experimental spill study was successful in differentiating the short-term effects of a dispersed oil spill from that of an untreated oil discharge. A large amount of important information was generated by the study in this regard. A consequence of the limitations of an experimental study carried out in the field, however, is that it was not possible to account for and control all impinging variables. A full assessment of fate and effects has to use extrapolation and interpretation of the data generated. The study described here will attempt to define, in a controlled manner, a number of behavioural effect indices which were suggested in the 1981 BIOS field spill, as well as describe more broadly the responses of Arctic marine benthos to oil.

METHODS AND MATERIALS

Location

The field portion of this study was carried out at Cape Hatt in Eclipse Sound, N.W.T. (72°28'N, 79°50'W), at the location of the 1981 Baffin Island Oil Spill study. On-site laboratory experiments were designed to investigate the behavioural responses of three selected species of benthic invertebrates to chemically dispersed crude oil. These tank studies were conducted on the shores of Cape Hatt during the period of August through early September 1982.

Experimental Design

Holding and Species Parameters. A flow-through system was constructed on-site to provide a number of 50 L aquaria simultaneously with a continuous flow of seawater at a rate of approximately 100 mL/min per tank. Water originated offshore from an 8 m water depth (high tide), taken 1 m above the bottom sediment. During dosing periods, the flow-through system was temporarily interrupted and individual circulators were used on each test and control tank to recirculate the total water volume at a rate of 8 L/min.

Temperature and salinity were verified regularly and were found to be 6 ± 1°C and 26 ± 3 °/oo, respectively, throughout the experimental period. This was similar to conditions recorded in offshore waters where the test species were collected. Further normalization of holding conditions was approached by the use of subdued natural lighting in the onshore laboratory.

The three test species selected were two filter-feeding bivalves, *Mya truncata* and *Serripes groenlandicus*, and a surface deposit-feeder, the green sea urchin *Strongylocentrotus droebachiensis*. All three species were collected by divers in 7 m water depths off the western shore of Ragged Island, a site near Cape Hatt but removed from potential oil contamination during the 1981 experimental spill. The test animals were transferred to the field laboratory, where they were acclimated in the flow-through seawater system for at least 7 days prior to the exposure studies. Mortalities during this acclimation period were less than 3%. Fresh seaweed (*Laminaria* sp.) and broken shell material were supplied regularly to the urchins during the pre-exposure period. *Serripes groenlandicus* were kept in a 10 cm layer of washed and sifted coarse beach sand, while both *M. truncata* and *S. droebachiensis* were held without sediment in the test tanks.

Except as noted below, the three species were of a medium size range, as identified in previous BIOS studies (Cross and Thomson, 1981). *Mya truncata* were 4.6 + 0.4 cm, *S. groenlandicus* were 4.3 + 0.6 cm, and urchins were 4.6 + 0.5 cm. One test series also used small and large individuals (*M. truncata*, 2.7-4.4 + 0.3 cm; *S. groenlandicus*, 2.7-5.1 + 0.4 cm; *S. droebachiensis*, 3.0-5.4 + 0.3 cm). Holding densities were calculated to not exceed field densities and were limited to 20 individuals of medium size for each species per 50 L aquarium.

Dosing Protocols. Dispersed oil concentrations were prepared by dilution of a stock oil/dispersant mixture. This was prepared by vortex stirring of the BIOS-stock aged Lago medio crude oil with Corexit 9527, 1:10, in seawater, as a 25,000 ppm solution. All concentrations are expressed on a basis of weight of crude oil.

Eight experimental conditions were tested, as outlined in Table 1. In all instances, the dosing procedure was similar, with concentrations, exposure times and number or size of animals being varied in accordance with the intent of the test. Single 6-hour exposures were carried out to assess dose-responses or experimental variables. Sequential doses (three at 6 h each) were designed to correlate with conditions recorded in Bays 9 and 10 after the field spill experiment. Corexit was tested alone at one concentration. Other experiments were carried out to differentiate the effect of a probable partial loss of volatiles from the dispersed oil during the exposure period. A post-exposure period of 7 days was used to assess recovery. Controls for each species were monitored concurrently with the exposure experiments.

Sampling Scheme. Water samples were taken from each exposure system during the first 5-10 min, and approximately 2, 4 and 6 h after the addition of each oil dispersion. A further sample was taken 1 h and 12 h after the exposure periods, when the tanks had undergone a rapid flushing with clean seawater. These 50 mL samples were analyzed for hydrocarbons by real-time fluorometry. A few additional 10 mL water samples were taken during the exposures for gas chromatographic analysis.

Samples for tissue hydrocarbons were taken at the end of the exposure periods (6 or 18 h) and at 7 d. The soft tissues of five individuals of each species were removed and pooled as a single sample for each time period. The tissues were wrapped in aluminum foil, sealed in Whirl-paks, and frozen.

All glassware and instruments used for hydrocarbon residue samples were prerinsed and dried with high purity hexane-methylene chloride solvent.

TABLE 1 DOSING PROTOCOL

Experimental Condition	Concentrations (ppm)	Exposure Time (h)	Test Organisms[a]
Single exposure	0,0.5,5.0,50,100,500	6	MYA SER STR
Sequential exposure Bay 10 simulation	0.5/5.0/0.2	6 each	MYA SER STR
Sequential exposure Bay 9 simulation	10/100/5.0	6 each	MYA SER STR
Single exposure (covered and uncovered comparisons)	250	6 6	STR STR
Sequential exposure (covered and uncovered comparisons)	10/100/5.0	6 each	MYA SER STR
Single exposure (size comparisons)	250	6	MYA SER STR
Single exposure (predation test)	250	6	SER
Corexit exposure	50	6	MYA SER STR

[a] SER = *Serripes groenlandicus* MYA = *Mya truncata* STR = *Strongylocentrotus droebachiensis*

n = 20 per test, except 15 for size comparison tests.

Analyses. Water samples were analyzed by real-time fluorometry and by gas chromatography on stored samples. The fluorometric method used a Turner model 240 flow-through fluorometer, calibrated and blank adjusted before and during use. Dispersed Lago medio crude was used for calibration. All readings were carried out in the linear range of the fluoresence calibration, at times necessitating dilution of test samples with seawater. Reproducibility of duplicate samples was found to be 5% or less.

Water analysis by gas chromatography was used in a limited manner to obtain preliminary data on hydrocarbon fraction composition in the test systems and to serve as a check on total oil concentrations determined by fluorometry.

The analyses were carried out under contract by Seakem Oceanography Ltd., using a Hewlett-Packard Model 5830A gas chromatograph, equipped with a J & W fused silica column with a SE-30 stationary phase. Standard methods were employed for the characterization of hydrocarbons in hexane extracts of the 10 mL water samples. Hydrocarbon concentrations were expressed as ppm of crude oil, calculated on the basis of the C-21 to C-24 alkane peaks relative to an internal standard (cetylbenzene).

Tissue hydrocarbon residues were analyzed as follows. Extraction of the samples was carried out according to the method of Engelhardt et al. (1982). Fused silica capillary GC (GC^2) of an aromatic hydrocarbon fraction (f_2) obtained through alumina/silicic acid fractionation of the total extract was used (Boehm et al., 1982). Naphthalene (N), methyl (C_1) naphthalenes, ethyl/dimethyl (C_2) naphthalenes and trimethyl (C_3) naphthalenes were quantified. The ratio of C_3N to total aromatics, and in turn the ratio of total aromatics to total oil (as determined by a combination of electrobalance gravimetric measurement on total oil and aromatic (f_2) fraction and total C_3N peak area to total f_2 peak area) were used to convert C_3N to "total oil" values for neat oil. As each sample was analyzed by GC^2, the total amounts of N, C_1N, C_2N, C_3N, and alkylated benzenes were obtained directly from the GC^2 trace. The C_3N:total oil conversion was used to arrive at the "total oil" values reported for the animals.

A variety of behavioural responses were recorded and quantified. The choice of particular behavioural indices of petroleum effect was based on extensive observations of the three species during the acclimation periods, and was predicated on being both quantifiable and significant to the survival of the individual. Characteristics of the index behavioural responses are detailed in Table 2.

TABLE 2 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA*, *SERRIPES GROENLANDICUS* AND *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS

Target species	Behavioural Responses	Description
Strongylocentrotus droebachiensis	direct observations	
	cover	shell fragments and pieces of algae cover test on aboral surface
	attachment	attachment to glass of aquarium floor and sides by tube feet
	spine droop	depression of spine downward along test surface
	spine rigidity	"pincushion" orientation and loss of flexibility
	curling of tube feet	aboral tube feet showing curling of distal ends
	retraction of tube feet	aboral tube feet not existent
	stimulus response	
	tube feet	tube foot retraction following mechanical stimulus laterally on test
	spine	re-orientation towards source of mechanical stimulus laterally on test
Mya truncata	direct observations	
	ostial closure	closure of both inhalent and exhalent siphons
	siphon retraction	retraction of siphon to 1/2 or less of normal extended length
	stimulus response	
	siphon	siphon retraction following mechanical stimulus to siphon
	mantle	retraction of mantle and closure of shell following mechanical stimulus of mantle edge
Serripes groenlandicus	direct observation	
	buried	burial to depth where ostia are exposed
	ostial closure	closure of one or both ostia
	mantle gape	mantle edges not closed and shell gaping
	stimulus response	
	siphon	siphon retraction following mechanical stimulus to siphon

TABLE 3 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SINGLE TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES (cont'd)

Nominal Concentration[a] (ppm)	Time[b] (hours)	Test Species[c]	Measured Concentration (ppm)	
			Fluorometry	Gas Chromatography
250	6	MYA	225	- (96)
		SER	225	- (86)
		STR	200 (225)	269 (153)
500	6	MYA	310	307
		SER	290	-
		STR	290	-
	12	MYA	nd	-
		SER	nd	-
		STR	nd	-

[a] Calculated as dilution of Lago medio crude-Corexit stock dispersion.

[b] Elapsed time from start of 6-h continuous exposure period.

[c] MYA - *Mya truncata*; SER - *Serripes groenlandicus*; STR - *Strongylocentrotus droebachiensis*.

[d] Numbers in parentheses are concentration values from duplicate tests in which exposure systems were covered.

nd = not detectable

- = no data collected

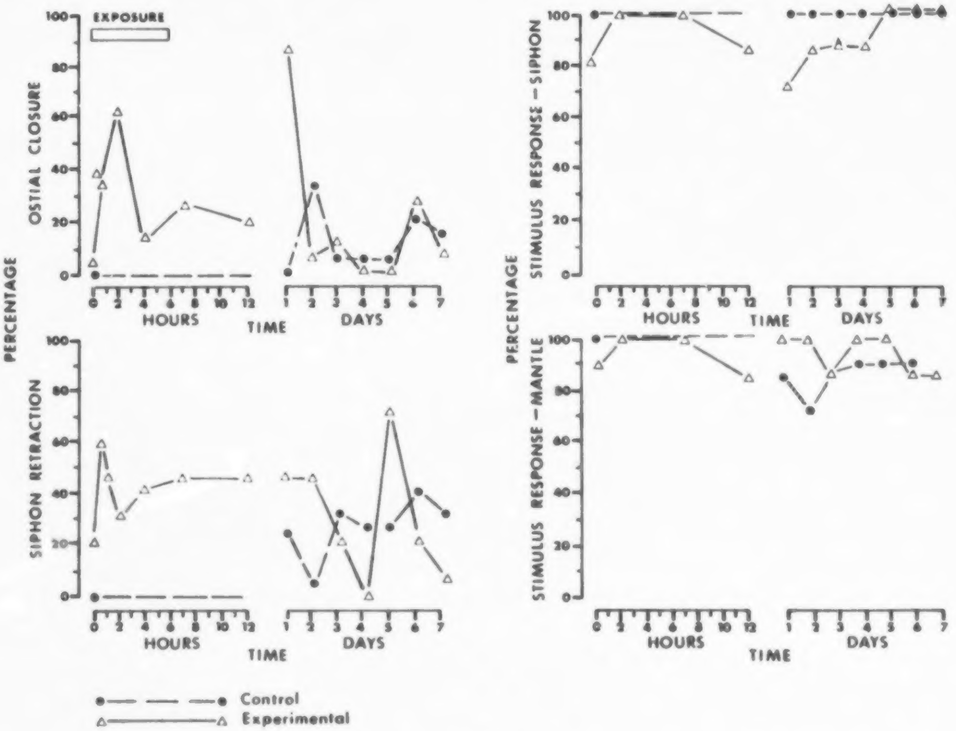

FIGURE 1 SELECTED BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* TO 50 PPM DISPERSED OIL

Quantitation of these responses was on the basis of proportion of the test population (n = 20) showing a change as related to exposure concentration and elapsed time. A standard point of comparison was the time at which 50% of the starting population showed a response (ET_{50}). Recovery was assessed as that point in elapsed time at which the proportion of animals showing the response had returned to pre-exposure levels. The reported ET_{50} and recovery time values were obtained from data plots made for each species and exposure test, comparing percentage of test population showing the response to elapsed time.

Behavioural changes in addition to quantified responses were also described. Such changes tended to be less consistent, or could not be observed to involve at least 50% of the test population at any concentration.

RESULTS

Exposure Concentrations

A comparison of nominal and fluorometry measured concentrations of crude oil hydrocarbons in the various test systems showed deviations of as much as 50% from the expected starting concentrations. The deviation was usually an increase in both single exposure (Table 3) and sequential exposure tests (Table 4). In all instances, the measured concentrations declined over the 6-h periods of static recirculated exposure to an average of two-thirds of starting concentrations. Subsequent extrapolations of concentrations to 6 h averages indicated that total exposures were very similar to nominal concentrations.

A small number of water samples were assessed by gas chromatography (GC) for both total oil concentration and fraction characteristics. Quantitation using C-21 to C-24 alkanes and an internal standard showed similar concentrations of oil in water as assessed by both methods. Both fluorometry and GC demonstrated similar declines in total oil concentration whether the systems were run covered or uncovered, as was the case for the majority of the tests.

Behavioural Responses

Mya truncata. This species responded to the presence of oil somewhat inconsistently, especially at the lower concentrations. Ostial closure and siphon retraction were common at concentrations above 10 ppm (Table 5; Figure 1). Loss of response capability to mechanical stimulation by retraction of the siphon or mantle was noted at concentrations of 50 ppm and above. This response tended to be latent. Recovery was rapid at low-level exposures even during the dosing period. Exposure to higher concentrations required longer recovery times. Corexit at 50 ppm elicited all four quantitated behavioural changes soon after exposure. Recovery times, however, were much shorter, with a return to normal behaviour within 1 d of the exposure.

The sequential dosing experiments suggested that responses were delayed relative to single exposures. These responses often did not occur during the period of highest concentration (for example, the 100 ppm phase (Table 6)); recovery required 1 to several days, as in the case of the single 100 ppm exposures. Neither size differences nor the effect of covering the exposure tanks could be differentiated in the *Mya truncata* tests.

Other behavioural changes were observed to occur as a consequence of oil exposure. At low concentrations, or early in the exposure periods, the diameters of siphon ostia tended to be increased. Occasional extensions of the foot were common. Elongation of the siphon was observed at high concentrations, especially late in the post-exposure period. No lethality was observed.

TABLE 3 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SINGLE TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES

Nominal Concentration[a] (ppm)	Time[b] (hours)	Test Species[c]	Measured Concentration (ppm)	
			Fluorometry	Gas Chromatography
0	0.1	MYA	nd	-
		SER	nd	-
		STR	nd	-
	12	MYA	nd	-
		SER	nd	-
		STR	nd	-
0.5	0.1	MYA	0.70	-
		SER	0.55	-
		STR	0.80	-
	6	MYA	nd	-
		SER	0.40	-
		STR	0.40	-
	12	MYA	nd	-
		SER	nd	-
		STR	nd	-
5.0	0.1	MYA	8.0	-
		SER	8.7	-
		STR	7.8	-
	6	MYA	6.0	-
		SER	6.4	-
		STR	6.8	-
	12	MYA	nd	
		SER	nd	
		STR	nd	
50	0.1	MYA	60	-
		SER	60	-
		STR	64	-
	6	MYA	26	26
		SER	22	-
		STR	23	-
	12	MYA	nd	-
		SER	nd	-
		STR	nd	-
100	0.1	MYA	140	-
		SER	128	-
		STR	136	-
	6	MYA	86	75
		SER	80	86
		STR	78	44
	12	MYA	nd	-
		SER	nd	-
		STR	nd	-
250	0.1	MYA	380	- (295)[d]
		SER	350	- (133)
		STR	310 (350)	320 (183)

TABLE 4 PETROLEUM HYDROCARBON CONCENTRATIONS IN WATER OF SEQUENTIAL TEST SYSTEMS, COMPARING NOMINAL CONCENTRATIONS TO VALUES DETERMINED BY REAL-TIME FLUOROMETRY AND BY GAS CHROMATOGRAPHIC ANALYSIS OF SELECTED SAMPLES

			Measured Concentration (ppm)			
Nominal Concentrations[a] (ppm)	Time[b] (hours)	Test Species[c]	Fluorometry		Gas Chromatogrpahy	
			ncv[d]	cv	ncv	cv
0.5/5/0.2	0.1	MYA	0.40		nd	
		SER	0.35		-	
		STR	0.40		-	
	6	MYA	0.20		nd	
		SER	nd		-	
		STR	nd		-	
	6.2	MYA	10		nd	
		SER	5.0		-	
		STR	6.5		-	
	12	MYA	-		nd	
		SER	5.0		-	
		STR	4.0		-	
	12.2	MYA	1.2		nd	
		SER	1.1		-	
		STR	0.65		-	
	18	MYA	1.0		nd	
		SER	1.0		-	
		STR	0.80		-	
10/100/5	0.1	MYA	12, 6.5	7.5	nd	nd
		SER	10, 8.0	8.0	-	-
		STR	10, 7.5	8.0	-	-
	6	MYA	8.5, 6.5	6.5	nd	nd
		SER	10, 5.0	6.2	-	-
		STR	6.5, 5.0	5.0	-	-
	6.2	MYA	150, 80	65	73, 159	130
		SER	150, 80	75	-	-
		STR	100, 90	65	-	-
	12	MYA	95, 65	50	110, 171	105
		SER	70, 50	50	-	-
		STR	65, 50	50	-	-
	12.2	MYA	10, 4.0	6.5	nd	nd
		SER	8.5, 5.0	6.5	-	-
		STR	8.5, 5.0	6.5	-	-
	18	MYA	7.0, 4.0	4.0	nd	nd
		SER	7.0, 3.7	4.0	-	-
		STR	7.5, 3.7	4.0	-	-

[a] Calculated as three dilutions of Lago medio crude-Corexit stock dispersions, presented sequentially.

[b] Elapsed time from start of three sequential exposure periods, each of 6-hour duration.

[c] MYA - *Mya truncata*; SER - *Serripes groenlandicus*; STR - *Strongylocentrotus droebachiensis*.

[d] ncv - tanks not covered during exposure period; cv - tanks covered during exposure period.

nd = not detectable; - = no data collected

TABLE 5 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

Exposure[a] Condition	Ostial Closure	Siphon Retraction	Stimulus Response - Siphon	Stimulus Response - Mantle
ET$_{50}$				
Oil				
0.5	NC	3 h	NC	NC
5.0	<0.5 h	NC	NC	5 d
50	1 h	1 h	NC	NC
100	0.5 h	0.5 h	NC	1 d
250 (cv, sml)	-	-	2 d	-
250 (cv, lg)	<2 h	-	-	-
500	-	-	12 h	6 h
Corexit				
50	<0.5 h	6 h	<0.5 h	<0.5 h
RECOVERY				
Oil				
0.5	NC	6 h	NC	NC
5.0	1 h	NC	NC	6 d
50	2 d	3 d	NC	NC
100	12 h	3 d	NC	2 d
250 (cv, sml)	1 d	1 d	>2 d	1 d
250 (cv, lg)	1 d	1 d	5 d	1 d
500	2 d	5 d	1 d	1 d
Corexit				
50	1 d	1 d	4 h-1 d	4 h-1 d

[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

NC = no change

- = no data, due to inacessibility of animals because of covered system or to inability to observe behavioural change in dispersion-clouded water

TABLE 6 BEHAVIOURAL RESPONSES OF *MYA TRUNCATA* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

Exposure[a] Condition	Ostial Closure	Siphon Retraction	Stimulus Response - Siphon	Stimulus Response - Mantle
ET_{50}				
0.5/5.0/0.2	NC	NC	NC	NC
10/100/5.0	3 h	6 h	1 d	13 h
10/100/5.0	7 h	NC	-	-
10/100/5.0 (cv)	7 h	NC	-	-
RECOVERY				
0.5/5/0.2	NC	NC	NC	NC
10/100/5	1 d	1 d	5 d	1 d
10/100/5	15 h	NC	-	-
10/100/5 (cv)	18 h	NC	-	-

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv.

NC = no change

- = no data

Serripes groenlandicus. At concentrations below 50 ppm, only ostial closure occurred as a response to oil (Table 7; Figure 2). Ostial closure showed a concentration-response relationship from 0 to 100 ppm, the time to affect closure decreasing with increased concentration. A discontinuity in this response occurred above 100 ppm, where ostia were closed in 50% of the test population only after several hours. At 250 ppm, both emergence from the sediment and an increased gaping of the mantle opening (and shell) became major responses. At 500 ppm, all behavioural indices were affected, with biphasic responses noted in mantle/shell gape, foot protrusion, and reaction to mechanical stimuli. The second phase of these responses was latent, occurring after the exposure period. Lethality as well was latent at 500 ppm, with an ET_{50} of 6 d. Recovery took 1 to several days, suggesting a dose response of increased recovery time with increasing concentrations. The data on the effect of differential sizes of test organisms to 250 ppm exposure were inconclusive.

Exposure to 50 ppm of Corexit resulted in emergence from the sediment, ostial closure, and mantle gape responses similar to the 500 ppm dispersed oil dose. Time to recovery from this exposure was shorter, however, and there was no lethality.

The 18-h three-phase exposure regime resulted in unique response patterns (Table 8). An initial 6-h exposure to 0.5 or 10 ppm resulted in an enhanced response to the mid-sequence high concentration, as compared to single doses of 5 and 100 ppm. Recovery as well was markedly delayed in the sequential exposure tests. Only the 500 ppm exposure resulted in lethality. The survivors recovered normal behaviour patterns. The use of tank covers to minimize evaporative hydrocarbon loss did not consistently alter the responses to sequential exposures. Most indices remained similar.

An additional response had to be inferred from the observations of ostial closure. Siphon retraction was a probable accompanying response which could not be quantified given the normal attitude of the bivalve. This attitude is characterized by burial to various depths in the sediment with only the tip of the siphon and ostia showing. Siphon retraction and forceful closure were probable occurrences at concentrations of 50 ppm and greater, as evidenced by a high incidence of shell damage. Individuals which emerged from the sediment tended to be cracked along the margins of their valves. At times this involved as much as one-third of the shell surface, exposing soft tissues. Forceful closure of the two valves was an additional latent response during both the 500 ppm single dose and the 10/100/5 ppm sequential exposure. Shell damage resulted from tight opposition of the valves, pinching an extruded foot. Increased locomotion occurred as a result of the extruded foot contacting the sediment and straightening rapidly to propel the shell. Locomotion was erratic and was observed primarily in emerged individuals early on during exposure to single concentrations of 250 and 500 ppm, and to the serial 10/100/5 ppm exposure. The style of locomotion was similar but was observed only rarely during the pre-exposure period.

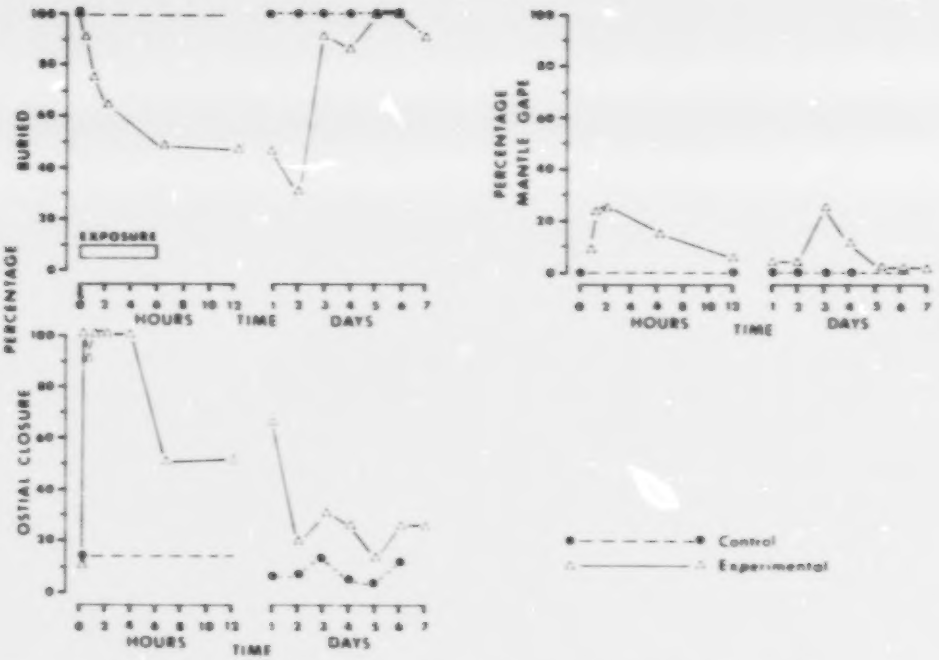

FIGURE 2 SELECTED BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* TO 50 PPM DISPERSED OIL

TABLE 8 BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

Exposure[a] Condition	Emergence	Ostial Closure	Mantle Gape	Foot Protrusion	Stimulus Response - Siphon	Lethality
ET$_{50}$						
0.5/5/0.2	18 h	6 h	NC	NC	NC	NC
10/100/5	13 h	<0.5 h	7 h, 2 d	7 h, 1 d	NC	
10/100/5	18 h	<0.5 h	7 h, 2 d	10 h	7 h	NC
10/100/5 (cv)	14 h	1 h	7 h, 2 d	0.5 h	-	NC
RECOVERY						
0.5/5/0.2	2 d	6 d	NC	NC	NC	NC
10/100/5	>7 d	5 d	13 h	12 h, 2 d	NC	NC
10/100/5	6 d	3 d	8 h, >7 d	13 h	3 d	NC
10/100/5 (cv)	4 d	1 d	8 h, >7 d	2 h	2 d	NC

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as CV.

NC = no change

- = no data

TABLE 7 BEHAVIOURAL RESPONSES OF *SERRIPES GROENLANDICUS* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

Exposure[a] Condition	Emergence	Ostial Closure	Mantle Gape	Foot Protrusion	Stimulus Response - Siphon	Lethality
ET$_{50}$						
Oil						
0.5	NC	6 h	NC	NC	NC	NC
5.0	NC	1 h	NC	NC	NC	NC
50	6 h	<0.5 h	NC	NC	NC	NC
100	12 h	<0.5 h	NC	NC	NC	NC
250 (cv, sml)	6 h	<5 h	1 d[b]	NC	-	NC
250 (cv, lg)	6 h	<6 h	3d[b]	NC	-	NC
500	4 h	3 h	<0.5 h, 3 d	<0.5 h, 1 d	<0.5 h, 7 d	6 d
Corexit						
50	4 h	3 h	4 h	NC	-	NC
RECOVERY						
Oil						
0.5	NC	1 d	NC	NC	NC	NC
5.0	NC	2 d	NC	NC	NC	NC
50	3 d	2 d	NC	NC	NC	NC
100	3 d	2 d	NC	NC	NC	NC
250 (cv, sml)	5 d	5 d	5 d	NC	-	NC
250 (cv, lg)	3 d	6 d	5 d	NC	-	NC
500	>7 d	6 d	1 d[b], 7 d	2 h, 7 d	3 d	-
Corexit						
50	2 d	2 d	2 d	NC	-	NC

[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

[b] Indicates the maximum response shown by less than 50% of starting test population, generally 20-40%.

NC = no change.

- = no data, usually because of use of a covered test system.

Strongylocentrotus droebachiensis. The urchin was the most responsive benthic species examined in terms of the number of behavioural indices affected by oil. The most sensitive response was the loss of covering material as the aboral tube feet released pieces of macro algae and shell fragments (Table 9; Figure 3).

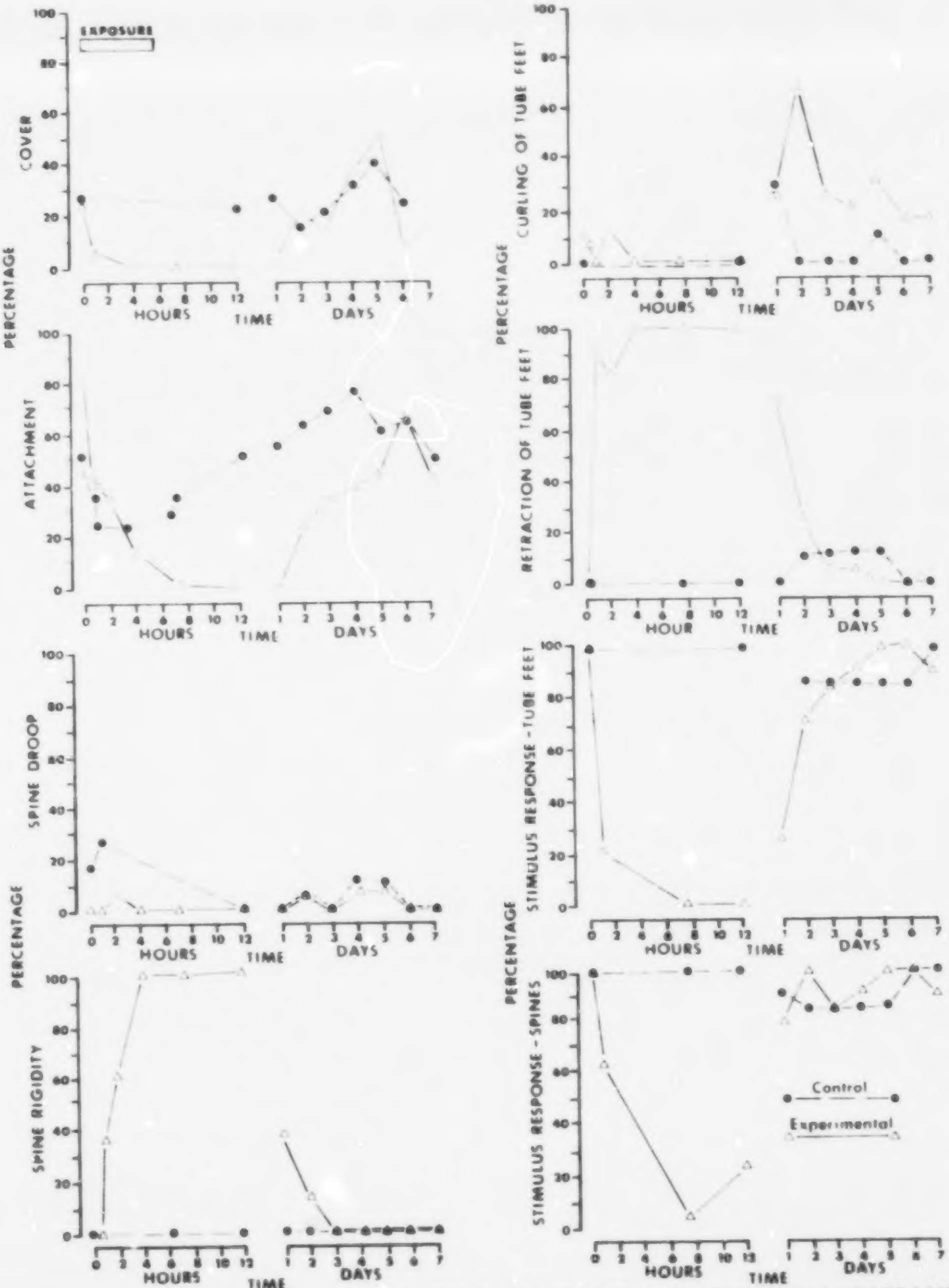

FIGURE 3 SELECTED BEHAVIOURAL RESPONSE OF *STRONGYLOCENTROTUS DROEBACHIENSIS* TO 50 PPM DISPERSED OIL

TABLE 9 BEHAVIOURAL RESPONSES OF *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS IN SINGLE TESTS

Exposure Condition[a]	Loss of Cover	Loss of Attachment Ability	Spine Droop	Spine Rigidity	Curling of Tube Feet	Retraction of Tube Feet	Stimulus Response Tube Feet	Stimulus Response Spines	Lethality
ET50									
Oil									
0.5	NC	NC	8 h[b]	NC	1 h	1 h[b]	NC	NC	NC
5.0	-	NC	4 h	3 h	4 h	4 h	5 h	5 h	NC
50	<1 h	3 h	NC	2 h	2 d	<1 h	<1 h	2 h	NC
100	2 h	3 h	-	3 h	2 d	<1 h	(2 h)	(2 h)	NC
250	<0.5 h	<0.5 h	0.5 h, 1 d	<0.5 h	0.5 h, 2 d	1 h	-	-	NC
250 (cv)	<0.5 h	1 h	0.5 h, 1 d	<0.5 h	2 d	<0.5 h	-	-	NC
250 (cv,sml)	1 h	1 h	<0.5 h	<0.5 h	<0.5 h, 3 d	<0.5 h	-	-	NC
250 (cv,lg)	1 h[b]	1 h	<0.5 h, 1 d	0.5 h	<0.5 h, 3 d	<0.5 h	-	-	NC
500	<0.5 h	1 h	1 d	<0.5 h	2 d	-	<1 h	<1 h	3 d
Corexit									
50	NC	<0.5 h	<0.5 h[b]	<0.5 h[b]	NC	-	NC	NC	NC
RECOVERY									
Oil									
0.5	NC	NC	2 d	NC	12 h	NC	NC	NC	NC
5	3 d	NC	NC	1 d	1 d	2 d	1 d	2 d	NC
50	4 d	3 d	NC	2 d	3 d	3 d	4 d	2 d	NC
100	4 d	3 d	NC	2 d	4 d	3 d	2 d	2 d	NC
250	3 d	>4 d	4 d	1 d	4 d	2 d	2 d	1 d	NC
250 (cv)	3 d	4 d	4 d	2 d	7 d	3 d	3 d	1 d	NC
250 (cv,sml)	3 d	5 d	1 h	3 d	1 h, 5 d	3 d	3 d	1 d	NC
250 (cv,lg)	3 d	4 d	1 h, 3 d	2 d	1 h, 5 d	3 d	3 d	1 d	NC
500	3 d	Nil	Nil	2 d	7 d	5 d	>5 d	>4 d	Nil
Corexit									
50	NC	12 h	2 h	2 h	NC	-	NC	NC	NC

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[a] 6 Hours of exposure to Lago medio crude oil or Corexit 9527 dispersions, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv; animal size medium except where noted as sml or lg.

[b] Indicates that maximum response shown by less than 50% of starting test population, generally 20-40%.

NC = no change; - = no data.

Loss of covering showed a concentration response beginning within 4 h at 10 ppm (Table 10) and occurring much earlier at higher concentrations. Loss of ability by the urchins to remain attached to the walls of the aquaria with their tube feet was also a sensitive response to oil and was also dose-related. Recovery of these tube feet functions required 3 to 5 d, irrespective of concentrations to 500 ppm. At 500 ppm, however, there was no recovery of attachment ability within the 7-d experimental period.

TABLE 10 BEHAVIOURAL RESPONSES OF *STRONGYLOCENTROTUS DROEBACHIENSIS* EXPOSED TO CRUDE OIL DISPERSIONS IN SEQUENTIAL TESTS

Exposure Condition[a]	Loss of Cover	Loss of Attachment Ability	Spine Droop	Spine Rigidity	Curling of Tube Feet	Retraction of Tube Feet	Stimulus Response Tube Feet	Stimulus Response Spines	Lethality
ET_{50}									
0.5/5/0.2	NC	7 h	3 h	1 h	12 h	7 h	7 h	7 h	NC
10/100/5	4 h	5 h	0.5 h	1 h	1 h	0.5 h	2 h	2 h	NC
10/100/5	-	6 h	5 h	6 h	5 h	6 h	-	-	7 d
10/100/5 (cv)	-	6 h	4 h	7 h	3 h	6 h	-	-	NC
RECOVERY									
0.5/5/0.2	NC	18 h	13 h	15 h	15 h	18 h	16 h	13 h	NC
10/100/5	4 d	3 d	2 h	1 d	6 d	6 d	6 d	6 d	NC
10/100/5	-	5 d	>7 d	1 d	9 h	1 d	1 d	1 d	Nil
10/100/5 (cv)	-	5 d	>7 d	2 d	13 h	1 d	1 d	2 d	NC

[a] 18 Hours of exposure to Lago medio crude oil dispersions, given in three sequential concentrations of 6 hours each, followed by 7 days of post-exposure observation; numerical entries identify concentration; all tanks not covered except where noted as cv.

NC = no change

- = no data

Curling and retraction of aboral tube feet was a further response to oil exposure (Table 9). At 250 ppm, the curling of the ostial ends of the tube feet was bi-phasic. Retraction of tube feet occurred rapidly at high doses, although not all tube feet were retracted simultaneously. A small number of oral and aboral tube feet often continued to attach the urchin to the glass surface. The higher the single exposure dose, the longer was the time required for recovery of these two indices, especially that of curling.

Changes in spine behaviour were observed at exposures to 5 ppm and greater; they occurred more rapidly and recovered more slowly with increasing exposure concentration. Drooping of aboral spines at times occurred in two phases, during both exposure and recovery periods. The "pincushion" effect characterizing spine rigidity tended to be a rapid response. Spine attitude recovery was generally more rapid than tube foot recovery.

Exposures to concentrations of 5 ppm and greater resulted in a loss of response capacity to mechanical stimuli, with ET_{50} times decreased from 5 h to less than 1 h (Table 9). Recovery times were not well correlated with exposure concentration, 1 to 5 d or more being required. Spine responsiveness recovered more rapidly than did tube foot responses. A lethal effect was recorded only when spine and tube foot responses to tactile stimulation were unobtainable. A 3-d ET_{50} for lethality was recorded for the 500 ppm single exposure.

Additional observations of *S. droebachiensis* responses to oil were made. Rapid linear movement along the substrate was noted in some instances at 50 to 250 ppm doses during the first few minutes following the addition of dispersed oil to the test systems. Also, a darkening in surface color was a common response to high-level exposures. Shedding of gametes occurred frequently within 2 d of exposure. Spines tended to drop off several days prior to a determination of death in the individual urchin.

No size specific effects were found in urchins. Exposure to 50 ppm of Corexit resulted in loss of adhesion and spine rigidity, but recovery of both functions was much more rapid than for any dispersed oil exposure.

The data shown in Table 10 suggest that 6 h of exposure to 0.5 ppm enhanced the effect of 5 ppm given in a subsequent dose, as compared to a 5 ppm single exposure. Since 10 ppm exposures were effective in eliciting all behavioural changes within a 6-h time period, it was not possible to differentiate the behavioural responses of 100 ppm single and sequential doses. A comparison test between covered and noncovered systems showed that the urchin response and recovery were similar.

Tissue Hydrocarbons

The results of tissue hydrocarbon determinations are presented in Table 11. Total aromatic concentrations averaged one-third of the total hydrocarbon levels. Total hydrocarbon values were mathematically derived from the sum of alkylbenzenes and naphthalenes, measured from the gas chromatograms, connected by an aromatic ratio of 0.0056. Total oil values were derived from a total aromatic to total oil ratio of 0.37.

M. truncata and *S. groenlandicus* tissues had a greater hydrocarbon load than did *S. droebachiensis* tissues when the samples were taken at 6 h of a single exposure, or 18 h of the sequential test. This relationship was reversed for the 7 d samples in which urchin tissue loads were not only greater than those of the bivalves, but also much higher than they were at 6 or 18 h. Urchin tissues additionally showed a greater capacity to take up alkyl benzenes during the dosing period, although the emphasis on these hydrocarbons tended to be gone in 7-d samples. An overview of tissue hydrocarbons demonstrated fractional compositions qualitatively similar to that of Lago medio crude oil (Figure 4).

DISCUSSION

Exposure Concentrations

Fluorescence analysis has shown itself to be a useful method for detecting hydrocarbons in water, especially when used as a real-time measure of experimental concentrations. The 0.5 ppm sensitivity limit is useful, since samples do not require any concentrating or other special handling, thereby minimizing procedural losses of volatile hydrocarbons in particular. The GC method, as employed in this phase of the study, generally verified the fluorometry concentrations. Both the covered and uncovered set-ups are likely to have undergone volatile losses. It is probable that the average one-third decline in starting concentration was mainly due to volatile losses. Nonetheless, averaging of measured concentrations over a 6-h exposure period showed values to be very similar to the nominal concentrations.

The choice of the range of exposure concentrations was predicated by the desire to encompass water concentrations of dispersed Lago medio crude as observed in the 1981 field spill. This condition was met by the series of single exposure tests. Closer similarity with the field concentration scenario was accomplished with the three-phase sequential exposure schemes. The 10/100/5 ppm concentration series was similar in level and sequence to what had been observed in Bay 9, the site of the dispersed oil spill, for the 18-h period subsequent to oil release (Green et al., 1982). The 0.5/5/0.2 ppm concentration sequence approximated the levels during the first 18 h post-spill in Bay 10, an area adjacent and down-channel from the dispersed oil spill site. In both the Bay 9 and 10 simulations, flushing with clean seawater after 18 h was appropriate to match the trace and undetectable concentration levels of hydrocarbons recorded in field observations after this time.

Behavioural Responses

The behavioural responses shown by the three species can be interpreted from the point of view of: direct toxicity effects of oil, the significance of these effects on survival to oil exposure, and finally interpreting the observations and conclusions originating from the field oil spills. In the latter case, meaningful correlations between this on-site controlled exposure study and the field spill cannot be made effectively until the benthic field data have been finally assembled and interpreted.

The description of behavioural changes in this study emphasizes ET_{50} values and time to recovery to pre-exposure behaviour. It should be recognized that other behavioural changes occurred which may either not have affected 50% of the test population or else were sporadic in occurrence. These will be described only to round out the observations of behavioural effects.

Mya truncata was found to be a difficult species for an assessment of oil effects. Behavioural changes tended to be "noisy" insofar as they were quite variable and easily set off by disturbances other than oil. A clear dose-response could not be discerned using the above indices, but the higher concentrations were certainly more effective in inducing behavioural changes and in delaying recovery times. The trend of this bivalve to close ostia rapidly, and thereby arrest water flow, filtration and oil input, may be considered an advantage in surviving exposure to oil in seawater. The loss of responsiveness to mechanical stimuli may be considered as a narcotization response, although other physiological causes such as neural control override or muscle fatigue may have been contributory. Altogether, *M. truncata* was more resistant to oil than either *S. groenlandicus* or *S. droebachiensis*.

TABLE 11 HYDROCARBON CONCENTRATIONS IN TISSUES OF *MYA TRUNCATA* (MYA), *SERRIPES GROENLANDICUS* (SER), AND *STRONGYLOCENTROTUS DROEBACHIENSIS* (STR)

			µg/g wet weight						
Exposure Condition[a]	Time	Species	ΣAB	N	ΣC_1N	ΣC_2N	ΣC_3N	Total Aromatic	Total Oil
0	6 h	MYA	0.08	0.001	0.001	0.004	0.050	8.9	24
		SER	nd	nd	nd	nd	nd	nd	nd
		STR	nd	nd	nd	nd	0.093	17	44
0.5	6 h	MYA	nd	nd	nd	nd	0.028	5.0	13
		SER	nd	nd	nd	0.011	0.032	5.7	15
		STR	nd	nd	nd	nd	0.116	21	55
5	6 h	MYA	0.36	0.017	0.120	0.267	0.269	48	130
		SER	0.64	0.024	0.194	0.457	0.455	81	217
		STR	nd	0.005	0.063	0.059	0.137	25	65
50	6 h	MYA	0.04	0.009	0.271	0.701	0.755	135	360
		SER	0.12	0.01	0.33	0.91	0.76	136	360
		STR	3.5	0.03	0.34	0.56	0.33	59	160
100	6 h	MYA	nd	nd	0.10	0.61	0.50	89	240
		SER	nd	0.1	0.21	0.60	0.37	66	180
		STR	nd	0.01	0.22	0.12	0.06	11	29
250	6 h	STR	nd	nd	0.03	0.03	0.04	7.7	21
250 (cv,lg)	6 h	MYA	nd	nd	0.23	0.53	0.38	67	180
		SER	nd	nd	0.26	0.67	0.44	79	210
		STR	nd	nd	0.01	0.09	0.04	7.0	19
250 (cv,sml)	6 h	SER	nd	0.01	0.12	0.22	0.12	22	59
		STR	nd	nd	0.70	0.10	0.08	14	37
500	6 h	MYA	0.05	0.01	0.54	1.9	1.5	270	710
		SER	1.7	0.16	1.2	2.1	1.1	200	540
		STR	0.5	0.05	0.30	0.20	0.06	11	31
0.5/5/0.2	18 h	MYA	nd	nd	nd	nd	0.03	5.9	16
		SER	nd	nd	nd	0.04	0.27	48	130
		STR	nd	nd	0.04	0.06	0.04	7.9	21
	7 d	MYA	0.01	nd	0.01	0.02	0.10	17	45
		SER	nd	nd	nd	0.01	0.05	8.4	22
		STR	nd	nd	nd	0.18	0.45	81	220
10/100/5	18 h	MYA	0.03	0.36	0.42	1.6	1.3	240	630
		SER	nd	nd	0.26	1.2	1.1	200	530
		STR	nd	nd	0.11	0.48	0.32	56	150
	7 d	MYA							
		SER	nd	nd	nd	0.10	0.31	55	150
		STR	0.08	0.01	0.24	0.88	1.1	190	510
10/100/5 (cv)	18 h	MYA	1.0	0.05	0.58	1.7	1.1	200	540
		SER	0.39	0.05	0.05	0.18	0.20	37	99
		STR	2.7	0.12	0.58	0.52	0.13	23	61
	7 d	MYA	0.07	nd	0.32	0.31	0.72	130	340
		SER	nd	0.10	0.20	0.10	0.36	65	170
		STR	nd	nd	0.08	0.48	0.80	140	380

TABLE 11 HYDROCARBON CONCENTRATIONS IN TISSUES OF *MYA TRUNCATA* (MYA), *SERRIPES GROENLANDICUS* (SER), AND *STRONGYLOCENTROTUS DROEBACHIENSIS* (STR) (cont'd)

Exposure Condition[a]	Time	Species	µg/g wet weight ΣAB	N	ΣC$_1$N	ΣC$_2$N	ΣC$_3$N	Total Aromatic	Total Oil
10/100/5	18 h	MYA	2.7	0.11	0.73	2.0	1.2	210	570
		SER	0.03	0.01	0.43	1.9	1.8	320	860
		STR	2.2	1.0	0.50	0.56	0.24	43	120
	7 d	MYA	ND	ND	ND	0.01	0.10	18	47
		SER	ND	ND	ND	0.01	0.07	12	33
		STR	0.80	0.08	0.15	0.59	0.74	130	350

[a] In order: Exposure concentration (ppm); where indicated, cv specifies tanks were covered during exposure; animal size, large or small where indicated, otherwise medium size range.

nd = not detectable

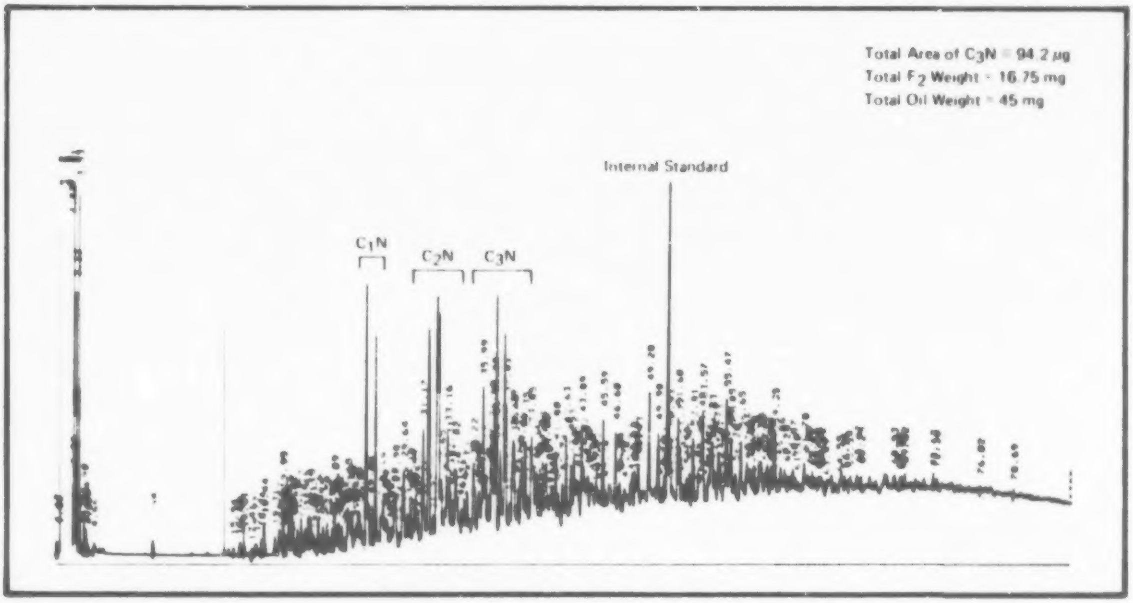

FIGURE 4 GC^2 TRACE OF AROMATIC FRACTION OF LAGO MEDIO CRUDE OIL

Serripes groenlandicus exhibited a more consistent and a wider behavioural response repertoire to oil exposure than did *M. truncata*. Both ostial closure and mantle/shell gape have relevance to the exposure of soft tissues to hydrocarbons. Closure of the ostia at even low concentrations of oil shut off filtration and limited the input of oil, explaining why the species showed few other responses at concentrations below 50 ppm. Conversely, rather than being an avoidance response, the mantle and shell gape which occurred both at higher concentrations and later in the experimental period are more likely to have been direct toxic effects. Both hydrocarbon narcosis and muscle fatigue are possible explanations.

The sporadic bursts of locomotion recorded at higher concentrations may be expected to expose sensitive tissues to oil. Exposure of soft tissues would also result from shell damage. The possibility of increased predation on the bivalve because of its emergence from the sediment, shell gaping, and shell damage has to be considered as a potential oil exposure effect on the benthic population. The decreased capacity to respond normally to tactile stimuli, as shown during exposure, suggests an early narcotizing effect. The latent recurrence of this negative response is more likely to have been of pathological origin.

Sequential dosing in *S. groenlandicus* pointed out that while the first low concentration phase was innocuous, similar to single exposures at the same concentration, a second exposure at a higher concentration elicited a markedly greater response than what would have been predicted from single exposures. This type of sequential exposure and corresponding response is similar to the situation reported for Bays 9 and 10 following the 1981 spill at Cape Hatt. Emergence and shell/mantle gaping were outstanding behaviour indices. The simplest explanation for the sensitivity of the species to sequential exposures may be that the animal has only a limited capacity to remain with shells closed. Once this time is exceeded (somewhat longer than 6 hours), the valves open and soft tissues become exposed to oil.

Strongylocentrotus droebachiensis served as a useful benthic species in which to observe the behavioural effects of dispersed crude oil. It was sensitive, showing responses even to 0.5 ppm of oil and demonstrating a fairly consistent dose response. A primary effect of oil exposure was debilitation of tube feet functions, causing loss of covering material and ability to adhere to substrate. The natural consequences of this may include an increased susceptibility to predation, displacement by currents, resulting in physical damage or removal from food source and habitat. This may be especially significant since this debilitating condition may last for several days even though the initial exposure may have been small and of short duration. The early responses of the tube feet, curling of aboral tube feet and loss of ability to respond to tactile stimulation, may result from the narcotizing effect of hydrocarbons in water. Distribution of hydrocarbons by the water vascular system of the urchin would generalize the response. Although interruption of water exchange was not verified, observations of the tube feet changes imply it was likely. Also, throughout the affected period, the peristomal membrane and the periproct regions displayed a sunken and flaccid appearance suggesting an impaired hydrostatic system.

A neuromuscular effect is implicated in the spine responses, again at least initially narcotic in nature. Spine drooping and spine rigidity alternated with each other and with a more normal radial but non-rigid arrangement. While spine drooping would increase the potential for damage and perhaps predation, spine rigidity would counter that effect. The response of assuming a more uniformly round, almost ball-like, appearance with rigid spines would, however, enhance the potential for physical displacement by currents.

Recovery of the spine system to respond to mechanical stimulation occurred sooner than did tube foot response, lending support to the suggestion that two different physiological systems were affected. Lethality occurred only during the 500 ppm single exposure test and during one of the Bay 9 simulating sequential tests. Recovery from the 500 ppm exposure was very limited, however; only two of the original 20 animals survived.

The responses to sequential dosing correlate well with divers' descriptions of the state of urchins in Bays 9 and 10 within a few days of the BIOS spill. Loss of adherence, narcotization, free movement in currents, and a decrease in the number of urchins in the spill area were all reported for that time period.

Tests of the effects of Corexit at 50 ppm, the amount used in 500 ppm oil dispersions, showed that all three species were responsive to the compound. The dispersant had a narcotizing effect on all three species, usually shortly after exposure. Recovery from all the noted responses for Corexit was rapid, however, and the overall effect of Corexit was much less than that of oil dispersions.

In all, the behavioural observations have shown that in these three major Arctic benthic species, the direct effects of short-term (6-h) exposure to dispersed oil are not likely to be fatal at 250 ppm or less. Behavioural changes may predispose these species, particularly *S. groenlandicus* and *S. droebachiensis*, to increased predation. Removal from habitat is another indirect effect, potentially most important to urchins.

Tissue Hydrocarbons

The tissue hydrocarbon part of this study was little emphasized in this phase of the program, and was limited in terms of both sample size and analytical detail. It was evident, however, that all three species accumulated crude oil hydrocarbons.

The two bivalve species showed maximum levels by 6 h or 18 h, corresponding to the end points of exposure regimes. By 7 d, these levels generally had decreased, even to background concentrations in some instances. In urchins, however, a very different response was noted. Samples of tissues taken at 7 d showed an increased accumulation of hydrocarbons. The source of these is likely to have been from residues accumulated on the external body surface which were then absorbed even during the recovery period. This pattern may serve to explain the latent mortalities in the test populations. Further, an emphasis on volatile hydrocarbons such as the water-soluble alkyl benzenes in the 6 h samples may have been a major factor in the rapid early narcosis which was recorded for urchins.

The pattern of accumulation and release observed in these three species is the same as that observed in the field following the experimental spill (Boehm et al., 1982). The actual levels do not and cannot be expected to correlate since sampling times were not the same. The higher values recorded in this study at 6 h as compared to the first post-spill samples taken in the field may be attributed to differences in sampling times. During the tank study, sampling was carried out immediately after the oil exposure, whereas field study samples were taken 1 to 4 d after exposure.

A further phase of the study program is planned to define hydrocarbon uptake and clearance characteristics, and correlate them with the behavioural effects of dispersed oil exposure.

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